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Exceptional Method Application for BamCore Prime Wall

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Exceptional Method Application for BamCore Prime Wall

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1. Request for Approval Under Section 10-109 for an Exceptional Method

BamCore, LLC requests approval under Section 10-109 of (2016) Title 24, Part 6, Article 1 as an exceptional method for calculating the performance of a new type of wall assembly called "BamCore Prime Wall." BamCore, LLC is the manufacturer of the BamCore Prime Wall, which is composed of two laminated veneer bamboo panels providing structural and thermal integrity (see Section A) using highly sustainable materials. We believe that we have adequately demonstrated that this product is a superior alternative to traditional wall framing methods and deserves to be properly modeled so that its true benefits can be realized for Title 24 energy compliance. We believe that it can be an important part of helping California achieve its energy conservation and greenhouse gas reduction goals. We propose that this wall system be generically referred to as "*Dual Panel Hollow (DPH) Wall*" in any CEC publication, software, or compliance document.

BamCore's Prime Wall has been used in low-rise construction for several years and is code compliant under the International Residential (Building) Code and the International (Commercial) Building Code. BamCore's Prime Wall code compliance report was issued by DrJ Engineering, an ANSI ISO/IEC 17065 accredited certification body. DrJ prescribed a rigorous path of testing that BamCore completed at various ISO 17025 accredited testing laboratories[1]. In addition, to maintain active compliance under the building codes, BamCore must maintain a comprehensive in-house QA/QC program that is reviewed quarterly by an ISO 17020 Inspection Agency.

This application presents justification for modifying current energy code compliance software, CBECC-Res, to properly and accurately model the thermal properties of BamCore Prime Wall. The current compliance software uses a "safe workaround" that does not adequately measure the wall system's performance. For example, CBECC-Res requires the U-factors and heat capacities of the individual assembly components, which are expressed inaccurately, for the two parallel bamboo panels of the BamCore Prime Wall. This application provides test results from certified laboratories as justification for inclusion of these values, as well as certified test results for complete wall assemblies to support and justify the overall values calculated using individual components.

The current Title 24 compliance software also requires a typical framing factor for each wall assembly modeled. This application provides a calculation for the framing factor for this wall system using the same method of calculating framing factors for other types of walls.

Proper modeling of these wall assemblies will not only require the appropriate material choices to be made in the software, but due to their unique components, the software will need to be modified to allow the selection and specification of the two parallel panels. This application provides specific recommendations for this modification.

Quality Insulation Installation (QII) is an important element of the Building Energy Efficiency Standards and the BamCore Prime Wall. BamCore, LLC is including its own insulation guidelines in the form of a Technical Bulletin (attached as an appendix to this application) to support and enhance the QII verification requirements of Reference Appendix Section RA3.5. This application includes a justification for why the current RA3.5 protocols are adequate for BamCore Prime Walls.

[1]See supporting documentation titled "BamCore TER" Section 2, "Applicable Codes and Standards."

2. Introduction

A. Description of BamCore Prime Wall[2]

The BamCore Prime Wall is composed of two parallel Laminated Veneer Bamboo (LVB) panels forming the interior and exterior faces of the wall assembly. These load bearing panels are fastened to wood framing at the top and bottom of the wall assembly, as specified by approved structural construction drawings (typically 2x6 top and bottom plates, but other sizes are allowed). Contiguous panels are fastened to each other using half-lap joints. Blocking between panels is added per specific job requirements, depending on the length and height of the wall. This blocking is vertical and does not span the entire height of the wall, making it unique compared to typical framed assemblies.

During design, the Registered Design Professional (RDP) will determine the need for structural blocking depending on the building's design and site constraints. The blocking can either be 50% or 85% of the height of the wall. This blocking is usually centered and has an opening above and below it between the two adjoining wall panels, allowing for a greater amount of installed insulation. This blocking is only needed for long sections of a wall, 8 feet or more, with no framed openings. This blocking is not load bearing and is purely to connect the inner and outer panels (Figure 2-1). Even with blocking, this unique configuration results in superior U-factors when compared to typical framed walls due to extremely low framing factors and greatly reduced thermal bridging.

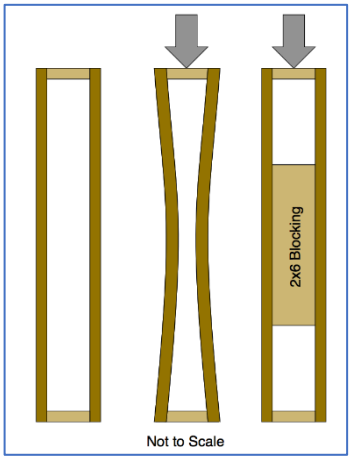

Figure 2-1

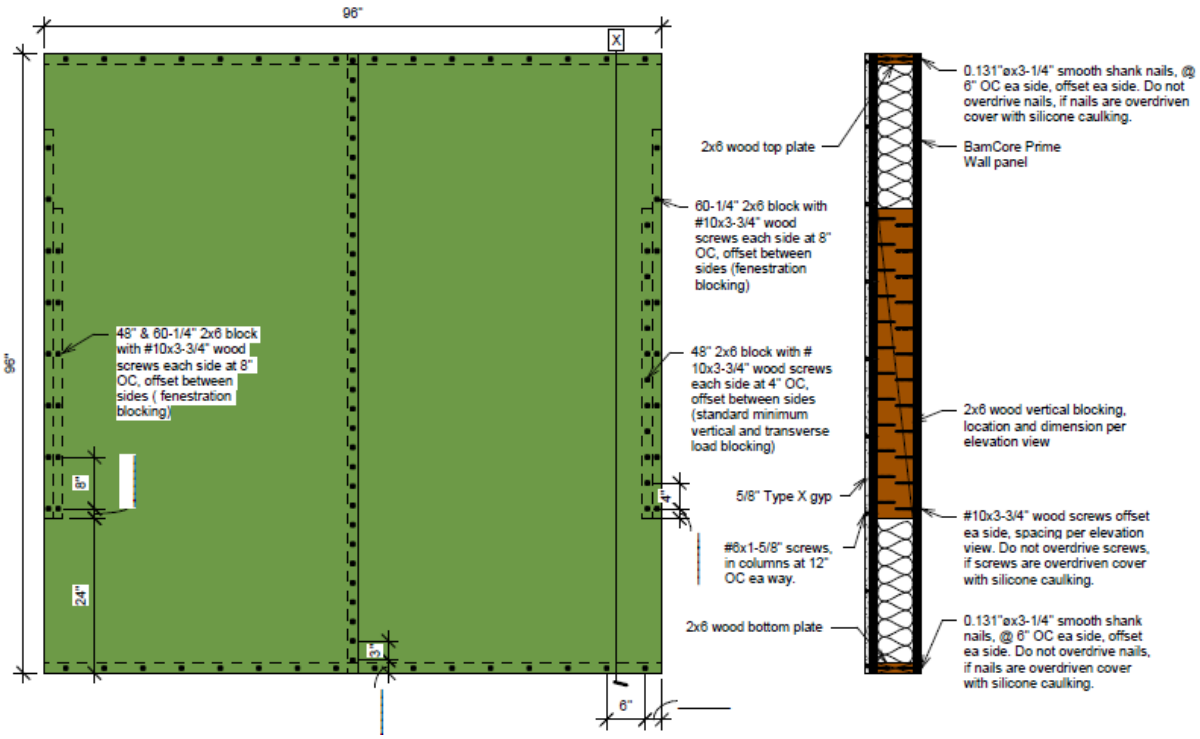

Figure 2-2: BamCore Prime Wall, Elevation View and Section

[2]Description of BamCore Prime Wall: See supporting documentation titled "BamCore TER."

Individual BamCore Prime Wall Panel Compositions:

The panels consist of multiple Laminated Veneer Bamboo (LVB) layers covered with nominal ⅛" Douglas fir veneer on both faces. The panels have a nominal thickness of 1¼" (Figure 2-3).

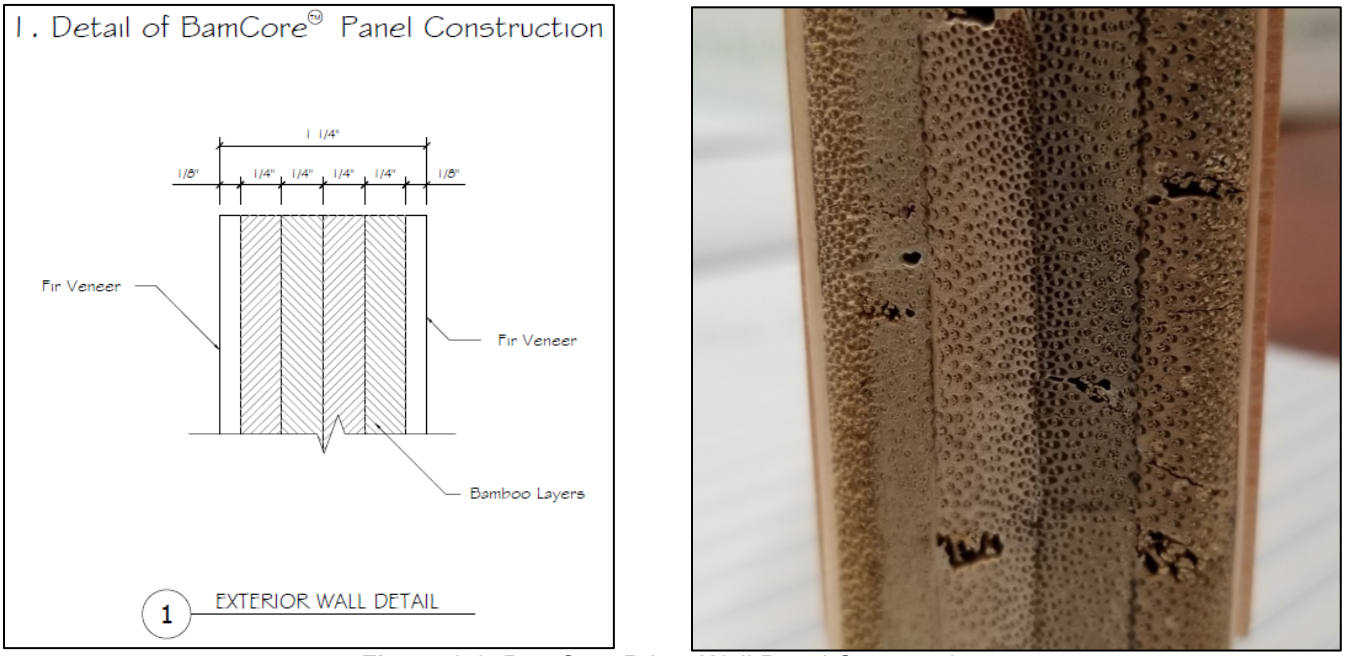

Figure 2-3: BamCore Prime Wall Panel Construction

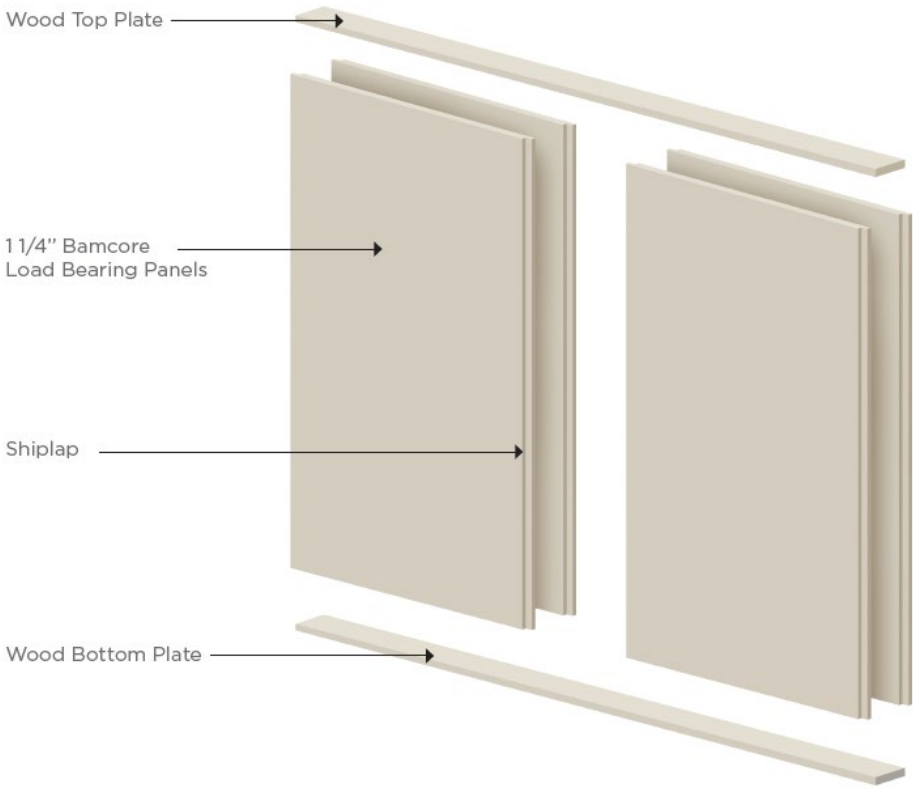

Figure 2-4: BamCore Prime Wall Typical Assembly

The BamCore Prime Wall may be designed with top and bottom plate widths that allow outer wall dimensions from 8" to 13¾".

Individual BamCore Prime Wall panels are manufactured with routed edges to form half lap joints at adjoining panel edges, from top to bottom. The half lap joint is $1^1/_2$" wide and half the thickness of the panel (Figure 2-5).

Contiguous panels within walls are connected at vertical joints with a half lap joint and 1¼" nails or screws.

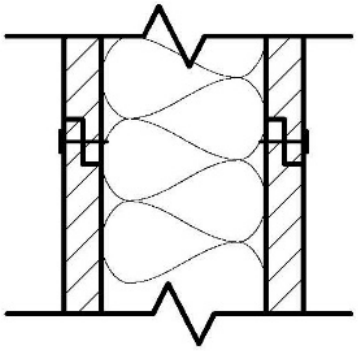

Figure 2-5: Prime Wall Panel Half Lap (Top View)

B. Durability

The bamboo and wood panels are manufactured to the structural load bearing compliance requirements of the California Building Code (CBC). Panels are composed of lingo-cellulosic structural fibers of known strength, and the panels can be expected to exhibit durability typical of structural wood panels.

C. Conditions of Use and Responsibilities[3]

To ensure consistency of production, this product is manufactured under a third-party quality control program (Columbia Research & Testing, an IAS ISO/IEC 17020-2012 accredited agency) in accordance with IRC Section R104.4 and R109.2, and IBC Section 104.4 and 110.4.

[3]Conditions of Use and Responsibilities: See supporting documentation titled "BamCore TER" Section 9.

3. Physical Properties

A. Dimensions, Panel Sizes, Framing Factors, Materials

1. Typical thicknesses: The panels have a nominal thickness of 1¼". Actual thickness is up to 1.28".
2. Typical panel lengths, heights, and thicknesses (Note: Panels can be cut to smaller sizes as needed per RDP):
   - 4' x 8' x 1¼"
   - 4' x 9' x 1¼"
   - 4' x 10' x 1¼"
3. Typical framing spacing – vertical and horizontal, framing factors. RDP will determine blocking requirements[4].

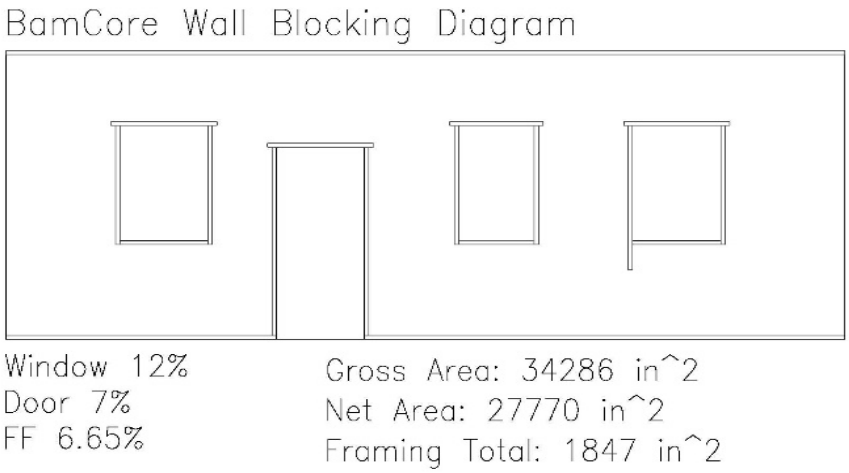

Figure 3-1: Typical wall used to calculate framing factor

- The framing factor of the exterior wall was derived by assuming a 12% window area and 7% door area. A conservative amount of required blocking for the BamCore Prime Wall was determined from this assembly and used in the calculation. The blocking provided by the doors and windows in the wall that was used to calculate the framing factor far exceeds the 50% or 85% blocking required for a typical long section of wall without openings. The assumed percentage of window and door areas was derived from the document "Characterization of Framing Factor for Low-Rise Residential Building Envelopes in California" (Figure 3-1), which was prepared for the California Energy Commission by Enermodal Engineering Limited, in association with Chitwood Energy Management, dated November 2001[4]. This is consistent with wall framing configurations used to calculate framing factors for other wall assemblies used by the CEC. The following represents the calculated typical exterior wall framing factor: (1847/27770) = 6.65%.

4. Materials of load bearing panels, framing, and insulating materials:
   - The panels consist of multiple Laminated Veneer Bamboo (LVB) layers covered with nominal ⅛" Douglas fir veneer on both faces with a nominal thickness of 1¼".
   - Top-bottom wood plates are determined by RDP per specific job requirements.
   - Insulating materials: Any type of blown-in insulation or batt insulation may be used per specific job requirements determined by the RDP.

[4]Typical framing spacing – vertical and horizontal framing factors: See supporting documentation titled "Characterization of Framing Factors for Low-Rise Residential Building Envelopes in California," which was prepared for the California Energy Commission by Enermodal Engineering Limited, in association with Chitwood Energy Management, dated November 2001.

B. Tested Assembly Air Permeability, U-factors, and Resistance

Assembly Thermal Performance Test Report for BamCore, LLC by Intertek. York, PA. Test report #I5420.01-109-44 per ASTM E283. Report issued 07/09/18 and report # I4810.03-116-46 RO per ASTM C1363-2011. Report issued 07/09/18.

- Assembly tested: framing factor 6.65%, two 1¼" panels with 2x6 top and bottom plate, 8" overall thickness. The 5½" cavity was filled with 3.5# density, blown-in dry cellulose insulation. Tested performance values resulted:
  - Air Permeability[5] ASTM E283-04(2012): at 1.57 psf. = .0003 cfm/ft²· infiltration and .0002 cfm/ft²· exfiltration
  - Thermal Transmittance[6] (U): 0.047 Btu/hr·ft²·degF
  - Specimen Thermal Resistance[6] (R): 20.33hr·ft²·degF/Btu

C. Tested Component Thermal Performance Information

Heat Flow Meter Thermal Transmission Test Report for BamCore, LLC by Intertek. York, PA. report # I6638.01-116-25 per ASTM C518-17. Report issued 08/17/18. U-factors, all materials, 1¼" panel (R@75degF).

- The sample used in these tests was a 12"x12" sample, which is consistent with the ASTM standards.
  - BamCore Prime Panel Material Average Thermal Conductance (C): 0.577 Btu/hr·ft²·degF (the average of two tests at 35 degF and 75 degF)[7]
  - BamCore Prime Panel Material Average Thermal Resistance (R): 1.735 hr·ft²·degF/Btu (the average of two tests at 35 degF and 75 degF)[7]
  - BamCore Prime Panel Material Average Thermal Resistance per inch (R/in): 1.355 (to be used in CBECC software calculations)[7]
- Density, specific heat, and calculated heat capacity, all materials, 1¼" panel
  - BamCore Prime Panel Material Average Density: 42.39 lbs/ft³ (to be used in CBECC software calculations)[7]
  - Bamboo Material Average Specific Heat: 1.75 J/g K. This converts to 0.418 btu/lb·degF heat capacity (to be used in CBECC software calculations) To obtain the thermal conductivity k of the sample, both the density and specific heat capacity need to be known. We have obtained the sample density through direct measurement, and the specific heat capacity via a numeric approximation as no verified information is available in the literature. Numeric approximations were made using the estimated thermal conductivity value and diffusivity value given by the Hot Disk analyzer software and the measured density of the sample. The specific heat capacity for Moso bamboo composites was estimated at 1.80 ± 0.38 J/kg K which is in agreement with the specific heat capacity of Moso bamboo [8], and with 1.75 ± 0.38 J/kg K for Guadua bamboo composites. Guadua is one of the primary bamboo species utilized by BamCore.[8]

[5]Air Permeability: See supporting documentation titled "ASTM E283 results."
[6]Thermal Transmittance and Specimen Thermal Resistance: See supporting documentation titled "ASTM 1363 results."
[7]Tested Component Thermal Performance Information: See supporting documentation titled "ASTM C518-17 results."
[8]Material Average Specific Heat Capacity: See supporting documentation titled "Thermal Conductivity of Engineered Bamboo."

	35 degF Mean Temp Test	75 degF Mean Temp Test	Average of two tests (calculated from test results)
Ave Thermal Conductance (C) (Btu/hr·ft²·degF)	0.561	0.593	0.577
Ave Thermal Resistance (R) (hr·ft²·degF/Btu)	1.78	1.69	1.735
Specimen Average Thickness (inches)	1.28	1.28	1.28
Specimen Average Density (lbs/ft³)	42.39	42.39	42.39
Ave Thermal Resistance per inch (R/in) (calculated from test results)	1.391	1.320	1.355

4. Modeling

A. Compliance Software (CBECC-res) Wall Assemblies

Below is a screenshot of the current construction data window used to create an exterior wall. Note the following:

- Construction Type – choices shown in Figure 4-2
- Cavity and Frame Paths – consistent with JA4 U-factor methodology, but with limited number of layers available
- Calculated Winter Design U-factor

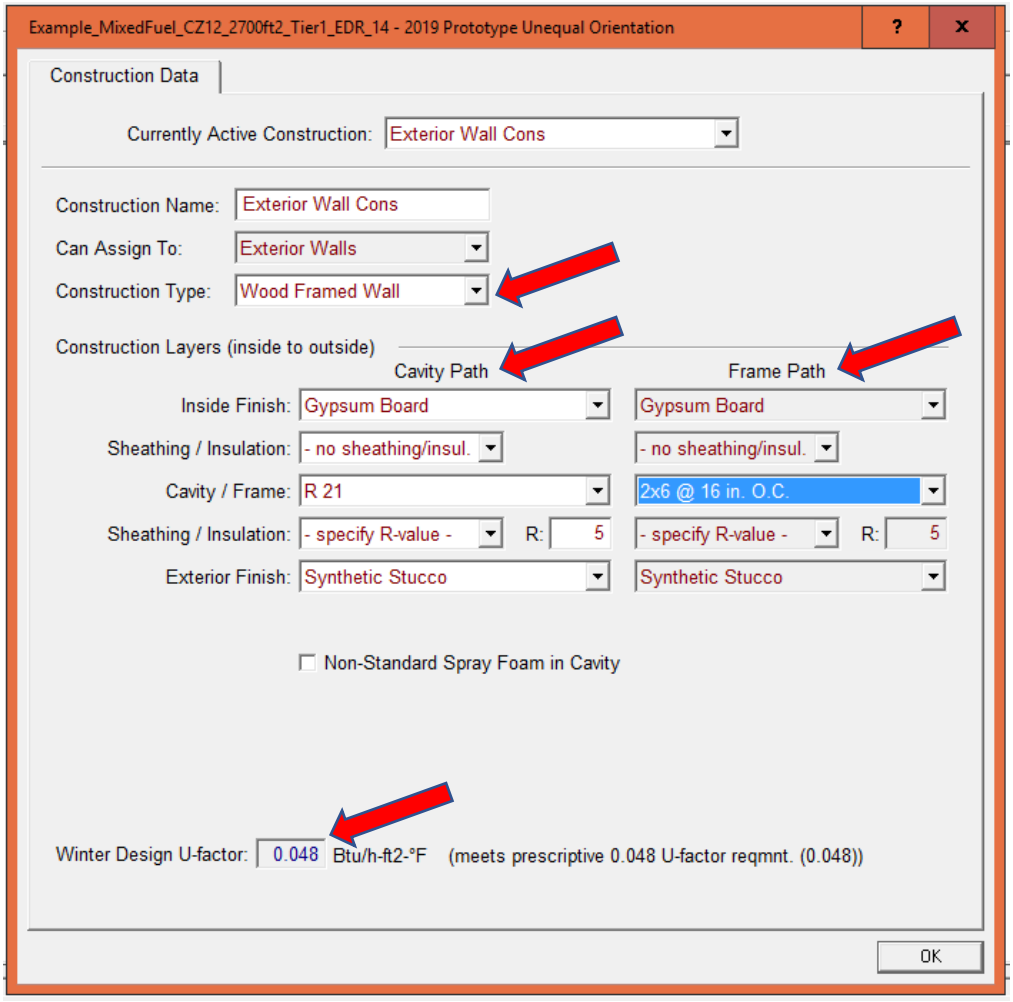

Figure 4-1

Performance factors not shown (internal to software):

- Framing factor
- U-factors for individual layers
- Interior and exterior air films
- Heat capacities of individual layers

The following choices appear for “Construction Type.”

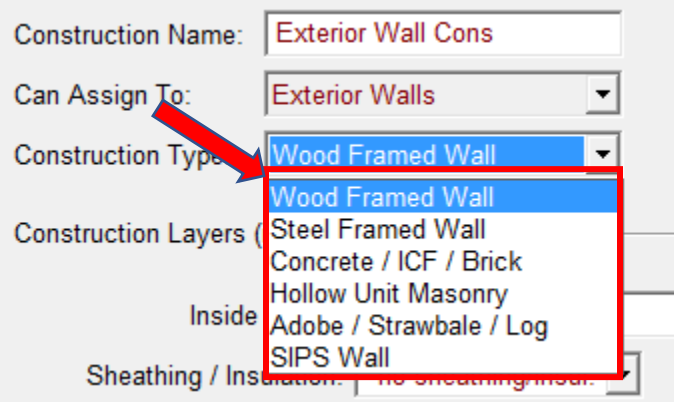

Figure 4-2

When the user chooses a different construction type—hollow-unit masonry, for example—the available choices change for the construction layers section.

Add *“Dual Panel Hollow (DPH) Wall”* as a choice in the Construction Type list, with the framing factor of 0.0665, justified in previous sections of this application.

Add the construction layers noted below. A *Dual Panel Hollow (DPH) Wall* is most similar to a standard frame wall in how it is assembled, but with more layers. We suggest a Construction Layers list similar to a wood-framed wall, with two additional layers to be added to the framing and cavity paths, which include appropriate drop-down choices:

- Inside Finish
- Sheathing/Insulation
- **Structural Panel** **<= Add**
- Cavity/Frame
- **Structural Panel** **<= Add**
- Sheathing/insulation
- Exterior finish

All but the two new Structural Panel layers are consistent with the layers for a wood framed wall, and the choices can be the same.

The only additional choice needed at this time for the two structural panels is the following:

- 1.28”-thick laminated bamboo panel

The thermal properties to be used internally in the software for this wall system, as justified in previous sections, are as follows:

- Heat capacity: 0.418 Btu/lb·degF.
- R-value: 1.7344. Note: The average tested R-value reported above in Section 3.C. was 1.735. Due to round-off error, this may be slightly high. BamCore proposes to use the tested R-per-inch value of 1.355 and the thickness of 1.28” to calculate the slightly lower value of 1.7344.

The images below show the U-factor calculation for a BamCore Prime Wall consistent with Joint Appendix Section JA4 for a BamCore Prime Wall assembly. Note: The U-factor calculated for this wall assembly is 0.0451 when using the values proposed above. This value is supported by certified testing data discussed in previous sections and is the value the software should calculate.

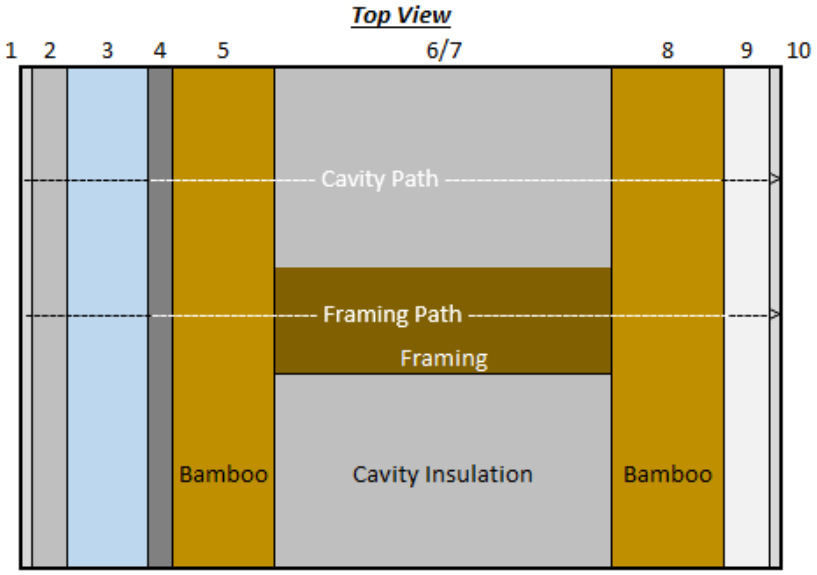

Figure 4-3

U-Factor Calculations for Wood Framed Assembly

Assembly Type: A1
Framing Material: wood

	Layer	Assembly Component	thickness	R-value/in	R-Values: Cavity Path Cavity R (R_C)	R-Values: Framing Path Framing R (R_F)
1	air film	**Outside air film**[1]	- -		0.17	0.17
2	siding	**3/8 inch 2-coat stucco**[1]	0.375		0.08	0.08
3	sheathing insul.	**none**	0	0	0	0
4	paper	**building paper (felt)**[1]			0.06	0.06
5	structural panel	**1-1/4" in bamboo laminate**[2]	1.28	1.355	1.7344	1.7344
6	cavity insul.	**dense pack cellulose**	5.5	3.5	19.25	
7	framing	**2x6 doug fir**	5.5	0.99		5.445
8	structural panel	**1-1/4" in bamboo laminate**[2]	1.28	1.355	1.7344	1.7344
9	interior finish	**gypsum board**[1]	0.5		0.45	0.45
10	air film	**inside air film**[1]	- -		0.68	0.68
		Total wall thickness:	8.935	Subtotal R:	24.1588	10.3538

Notes:
[1] Default values
[2] Nominal thickness

Framing Factor (FF%):	6.65 %	Assembly U-Factor:	0.0451
		Assembly R-Value:	22.1912
$1/R_C$	0.041392784		
1-FF%/100	0.9335		
$1/R_F$	0.096582897		
FF%	0.0665		

Figure 4-4

In summary, the BamCore Prime Wall is most similar to a typical framed wall. Some simple modifications to the CBECC-Res software will allow BamCore Prime Walls to be more precisely modeled and allow them to receive full energy credit more accurately depictive of their energy performance.

5. Verification of QII

A. Introduction

BamCore Prime Walls (aka DPH wall) allow insulation to be installed that can meet the verification requirements of Section RA3.5. BamCore Prime Walls can accommodate loose fill blown-in insulation, batt insulation, and blanket insulation. Even though BamCore Prime Walls do not have the framing studs normally used to support batt or blanket insulation, batts and blankets can be used, provided the installer uses professional fastening methods common to the industry, similar to methods employed in post and beam construction. In this case, the RA3.5 sections pertaining to batts and blankets apply without modification. Loose fill insulation is far more common for BamCore Prime Walls. The RA3.5 sections pertaining to loose fill insulation applies without modification.

To ensure insulation is installed correctly in the BamCore Prime Wall, and to help provide guidance to insulation installers for meeting the compliance requirements for QII, BamCore, LLC will provide a Technical Bulletin to clarify how these protocols apply specifically to this wall assembly and ensure the performance of the BamCore Prime Wall. A copy of the Technical Bulletin is included in the appendices of this application.

B. Justification

The current section that pertains to measuring R-value of loose fill insulation in walls is Section RA3.5.4.1.2 R-value Measurement Equipment, which states the following, in its entirety:

The HERS rater shall measure the installed thickness and density of insulation in at least six random locations on walls, roof/ceilings, and floors (i.e., six measurements per opaque surface type: wall, roof/ceiling, or floor) to ensure minimum thickness levels and the installed density meet the R-value specified on the Certificate of Compliance and all other required compliance documentation. For walls, measurement areas shall include low and high areas of the insulated assembly and the HERS rater shall verify density measurements are consistent with the manufacturer's coverage chart.

The purpose of this protocol is to provide a HERS rater with the tools and techniques needed to adequately verify the loose fill insulation has been properly installed and meets the intended R-value.

Loose fill insulation is typically installed using one of two methods: (1) A fabric or other material is stapled across the living-space side of the framing and insulation is blown or sprayed through the holes placed in this fabric, or (2) an adhesive is added to the loose fill material whereby the insulation stays in place until the interior finish (drywall) material is installed. A BamCore Prime Wall can be installed at the building site as a single exterior wall whereby plumbing, electrical, and insulation is finished prior to placement of the interior BamCore Prime Wall unit. The inner panel replaces sheet rock in typical framed construction. Some electrical and plumbing can be installed after the inner panel is set and before insulation, but it will be limited. Note: Nothing in the current QII protocol of section RA3.5.4 restricts the use or type of interior finish material (e.g., sheet rock/drywall as the interior side of the air barrier) as long as the required minimum number of insulation samples can be taken.

When an interior-side membrane is used with loose fill insulation, it is typically installed by making a small hole (less than 3” in diameter) in the interior containment barrier, inserting a hose, and blowing the insulation into the cavity. The installer must move the hose around so that the insulation completely fills the cavity. This must be repeated for every wall cavity. For 16” on center framing, this would be repeated for approximately every 14½”-wide section of wall, of which there could be several

hundred in a typical home. Poorly installed insulation typically results in areas where the insulation is missing or of inadequate density. This is alleviated by having the installer provide the calculations for how many bags of insulation will be blown into the calculated volume of the wall cavities. The HERS rater then performs a series of no fewer than six random density measurements in which they take a sample of the insulation of known volume, weigh it, and calculate the minimum pounds per square foot as specified by the manufacturer. (Note: There is no current specification in Section RA 3.5.4 for how big the individual sample should be. Common tools used for sampling are 3” to 6” in diameter. HERS raters will use 4” diameter sample holes for BamCore Prime Wall. These can be made by the rater using special tools or by someone else on-site as directed by the rater.)

The main difference between installing and inspecting insulation in the BamCore Prime Wall versus typical framed walls is that rather than using a fabric for the inner containment barrier, the BamCore Prime Wall uses the inner structural panel. (Note that in the *current* RA3.5 protocols, there is no requirement that the inner containment barrier be translucent.) The advantage that BamCore Prime Wall has over typical framed walls, in this regard, is that there are virtually no continuous top-to-bottom framing members (e.g., studs). Each wall section is a continuous open cavity from top to bottom and end to end, interrupted only by occasional partial vertical blocking and window and door framing.

For loose fill insulation, the Technical Bulletin for BamCore Prime Wall will detail mandatory inspection and sampling holes to ensure that the insulation integrity can be properly verified. The installer or HERS rater can request additional holes as needed. These installation and inspection holes, when used with procedures outlined in the Technical Bulletin for the BamCore Prime Wall, will exceed the minimum requirements of section RA3.5 protocols for typical framed walls and ensure the full thermal benefits of the BamCore Prime Walls.

6. Compliance Documentation

To ensure that HERS raters and enforcement personnel are aware that BamCore Prime Walls (DPH walls) are in general compliance with the energy code, we propose the following modifications to the Residential Compliance Manual and compliance documents.

A. Text for Compliance Manual

Add the following section:

Section 3.7.5 “Dual Panel Hollow (DPH) Walls”:

DPH walls are a type of structural wall assembly that at first appear similar to SIPS, but is quite different. They are more like a typical framed wall with extremely low framing factors. They consist of two parallel layers of laminated bamboo panels (or other substrate, like wood), an exterior panel, and an interior panel. At a typical thickness of 1¼”, each wall component is extremely strong and structurally stable. When delivered to the building site, they remove the need for most full-length, full-width studs and door and window headers, thereby dramatically reducing the amount of framing and allowing for more effective insulation coverage.

DPH walls are assembled in pieces. The exterior panel is set in place first and face-nailed to the bottom plate. All the electrical and plumbing can then be attached to the inside surface of the exterior panel, and insulation, such as batts or blankets, can also be installed. When the interior panel is attached, the top plate is installed and loose fill insulation can be blown into the empty wall cavity. Because various types of loose fill insulation have different densities and R-values per inch, it is important to model the correct one and make sure it is installed properly. DPH walls only apply to wall assemblies, not floors or roofs/ceilings. Batt and blanket insulation can also be used with a DPH wall assembly, provided proper fastening and support techniques are used prior to the interior panel being set in place.

The panels are precisely cut in a factory and shipped to the job site ready for assembly. Due to the extremely tight tolerances and overlapping joints, caulking and sealing is not required where the panels are joined using a ship lap joint, unless the project RDP directs otherwise. Sealing is still required where the outer panel meets the top and bottom plates, where the inner panel meets the top plate and any other penetrations in the outer panel. The bamboo panels qualify as air barriers[9]. The cavity between the panels can range from 5½” to as much as 11¼” in width, allowing cavity R-values from R-19 up to R-48. Assembly U-factors for various wall widths and insulation types can be calculated in the compliance software.

DPH walls are eligible for QII credits. The manufacturer shall provide specific instructions for how to apply the RA3.5 protocols and shall provide the means to take the minimum number of density samples to ensure compliance with the QII protocols.

[9]Air Permeability: See supporting documentation titled “ASTM E283 results.”

B. Edits to Compliance Documents (CF2Rs and CF3Rs)

CF2R-ENV-03 – **No changes**

CF2R-ENV-21 – **Add a Section L**, "Special Requirements for Dual Panel Hollow (DPH) Wall," with similar wording to Sections J and K. Or combine all three into one section.

J. Special Requirements for SIPs	
01	SIPs are considered an air barrier when properly sealed at top, bottom, sides and all penetrations.
02	Air barrier is continuous across all surfaces, including between SIPs and non-SIP sections.
The responsible person's signature on this compliance document affirms that all applicable requirements in this table have been met.	

K. Special Requirements for ICF	
01	ICF sections are considered an air barrier when properly sealed at top, bottom, sides and all penetrations.
02	Air barrier is continuous across all surfaces, including between ICF and non-ICF sections.
The responsible person's signature on this compliance document affirms that all applicable requirements in this table have been met.	

CF2R-ENV-22 – Item D01 conflicts with DPH wall, but it also conflicts with SIPS and ICF. **Add "Exception: Dual Panel Hollow (DPH) Wall, ICF and SIPS."**

D. Wall Adjacent to Unconditioned Space	
01	Insulation quality was verified prior to the installation of the interior air barrier (typically gypsum board).
02	Loose-fill and batt insulation is in contact with all six sides of wall cavities (top, bottom, back, left, right, front [to be installed later]) with no gaps, voids or compression. Exception: Where framing depth is greater than minimum required insulation thickness (e.g., R-19 batts

CF3R-ENV-21 – **Add a Section L**, "Special Requirements for Dual Panel Hollow (DPH) Wall" with similar wording to Sections J and K. Or combine all three into one section (similar to suggested change for CF2R-ENV-21).

J. Special Requirements for SIPs		
01	SIPs are considered an air barrier when properly sealed at top, bottom, sides and all penetrations.	
02	Air barrier is continuous across all surfaces, including between SIPs and non-SIP sections.	
03	Verification Status	☐ Pass - all applicable requirements are met; or ☐ Fail - one or more applicable requirements are not met. Enter reason for failure in corrections notes field below; or ☐ All N/A - This entire table is not applicable.
04	Correction Notes	
The responsible person's signature on this compliance document affirms that all applicable requirements in this table have been met unless otherwise noted in the Verification Status and the Correction Notes.		

K. Special Requirements for ICF		
01	ICF sections are considered an air barrier when properly sealed at top, bottom, sides and all penetrations.	
02	Air barrier is continuous across all surfaces, including between ICF and non-ICF sections.	
03	Verification Status	☐ Pass - all applicable requirements are met; or ☐ Fail - one or more applicable requirements are not met. Enter reason for failure in corrections notes field below; or ☐ All N/A - This entire table is not applicable.
04	Correction Notes	
The responsible person's signature on this compliance document affirms that all applicable requirements in this table have been met unless otherwise noted in the Verification Status and the Correction Notes.		

CF3R-ENV-22 - Item D01 conflicts with DPH walls, but it also conflicts with SIPS and ICF. **Add "Exception: Dual Panel Hollow (DPH) Wall, ICF and SIPS"** (similar to suggested change for CF2R-ENV-22).

D. Wall Adjacent to Unconditioned Space	
01	Insulation quality was verified prior to the installation of the interior air barrier (typically gypsum board).
	Loose-fill and batt insulation is in contact with all six sides of wall cavities (top, bottom, back, left, right, front [to be installed later]) with

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end
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BAMCORE TECHNICAL BULLETIN

BamCore Technical Bulletin

Protocols for Verification of Quality Insulation Installation (QII)

QII Protocols for BamCore Prime Wall (aka Dual Panel Hollow (DPH) wall)

(a) The following procedures detail the special installation and inspection protocols necessary to ensure compliance with the California Energy Commission's Title 24 Reference Appendices Section RA3.5 for Quality Insulation Installation (QII) of BamCore Prime Walls. These procedures must be followed in order to claim QII energy compliance.

(b) The insulation installer for the BamCore Prime Walls is to follow these procedures and a certified Home Energy Rating System (HERS) rater must verify its conformance for meeting the requirements of the following Sections.

(c) All applicable Sections of RA3.5 shall be strictly followed.

Thermal Specification

(a) BamCore Prime Walls are a composite building material manufactured as individual panels to be assembled on site into a dual panel. The panels contain a hollow wall for an insulative material to be blown into the cavity to fill the wall after all Mechanical, Electrical, Plumbing, and HVAC have been installed within the two wall panels. The exterior panel and the top and bottom plates are raised upright and braced first. The interior panel is attached *after* Mechanical, Electrical, and Plumbing are installed and *after* the HERS rater performs the framing inspection for continuous air barrier and sealing. In some situations, properly fastened and supported batt or blanket insulation may be installed prior to setting the interior panel. If not, any kind of approved loose fill insulative material can be blown into the cavity between two layers of structural panels, usually referred to as a "panel." The result is "panelized" construction versus traditional framed construction.

(b) BamCore Prime Walls combine some components of conventional building, such as partial blocks, posts and joists, insulation, vapor retarder, and air barrier.

(c) Common panel sizes range from 4x8 feet to 4x10 feet and have a structural panel thickness of 1.25 inches per panel. Panels are assembled over wooden top and bottom plates of 5.5 inches and larger widths. The top and bottom plates are placed between the bamboo panels and thereby establish the spacing between them and the thickness of the insulation.

(d) Panels are precut at the manufacturing facility to precisely fit the building's design characteristics. Openings for windows and doors are pre-cut into one or more panels, as well as all electrical, plumbing, and HVAC locations.

(e) BamCore Prime Walls are only used for the vertical building components (walls).

(f) BamCore Prime Walls will be used in conjunction with other traditional framed assemblies for floors, ceilings, and roofs.

(g) The R-value of a BamCore Prime Wall is dependent on the type of insulation used, its thickness, and, in the case of blown-in insulation material, the density of the insulation. The width of the cavity is specified by the architect and/or structural engineer. Specific product R-values are readily available from the insulation manufacturer.

Requirements for Walls

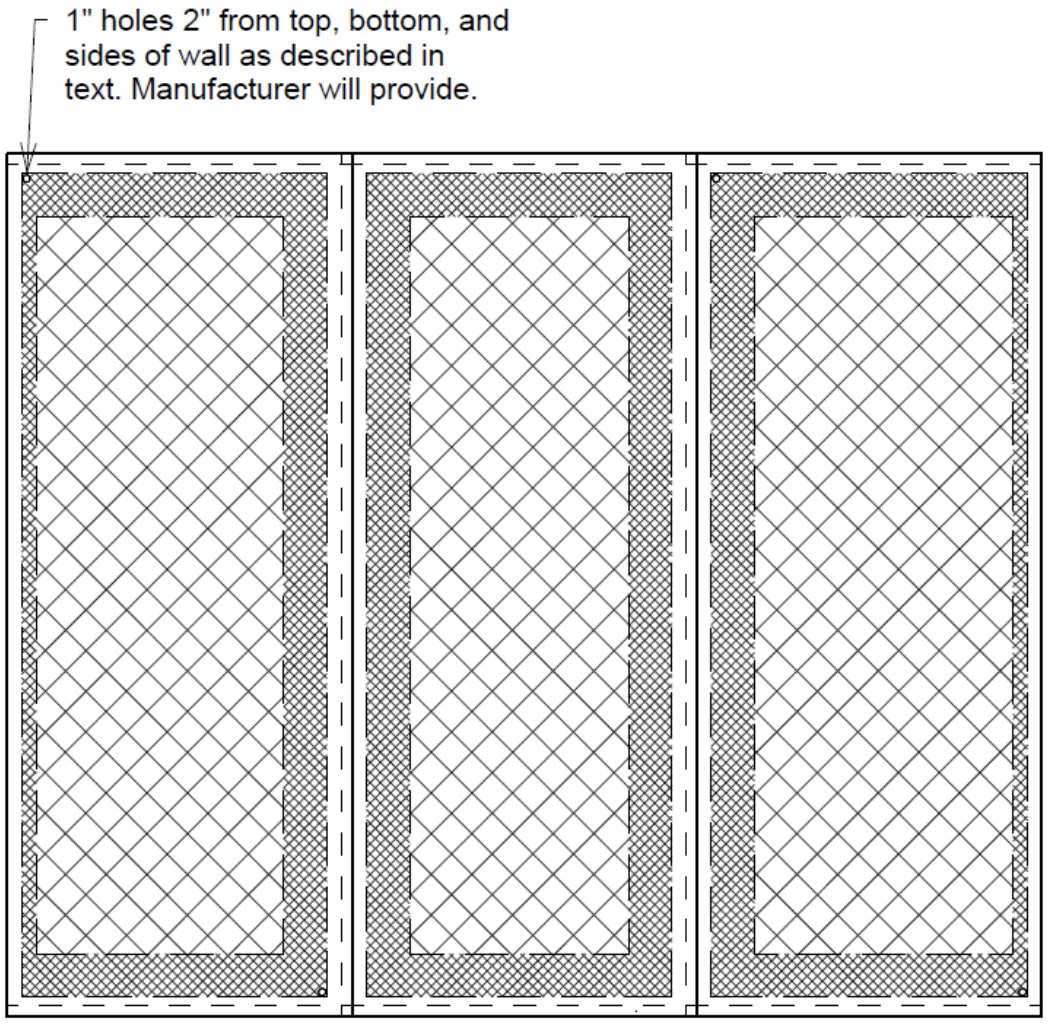
(a) Materials shall be installed according to manufacturer specifications and instructions in a manner that will meet the intended requirements of the QII verification process.

(b) Each individual panel of a BamCore Prime Wall is considered an air barrier; however, extension of the air barrier shall be made across all interconnections of panels, at window and door openings, and at all adjoining surfaces of different panel areas (e.g., where BamCore Prime Walls adjoin the floor and roof/ceiling).

R-value Measurement

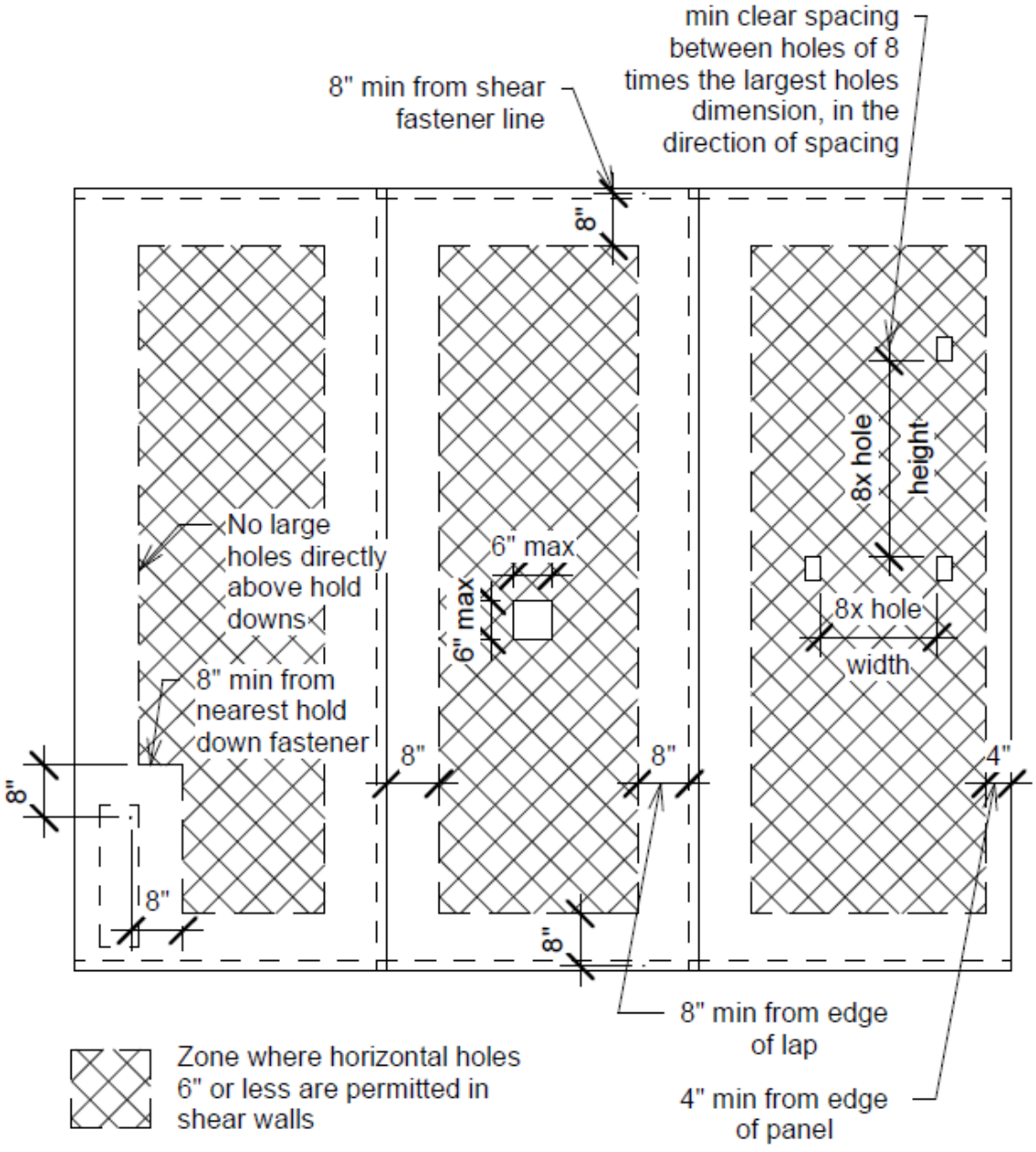
(a) The HERS raters shall verify the insulation material type and installed thickness of insulation in all BamCore Prime Wall panels and in all locations on walls where the manufacturer has provided access holes. The manufacturer will provide, at a minimum, two 1-inch-diameter access holes for every other 4-foot-wide panel. One hole will be within 2 inches of the top edge and one hole will be within 2 inches of the bottom edge. See Figure 1 – *1" Insulation Access Holes for HERS Rater*, below. The HERS rater will use these holes to ensure the insulation has completely filled the cavity by probing with a finger or non-metal probe. The HERS rater may request additional 1" access holes as needed. These holes are to verify that insulation has reached that point of the wall cavity.

(b) The HERS rater will take at least six random density samples per wall type (plate width or insulation type). Holes will be 3 to 4 inches in diameter. These holes will be patched later using a half-lapped cover up to 6 inches in outer diameter. (Note: This is the maximum size unless special permission is obtained from the manufacturer.) Cutting a hole, no larger than 4 inches in diameter allows a 1-inch lap of the patch material. The locations of each hole will be selected by the rater. Inspection holes shall be no less than 6 inches from the ends of a shear wall (Shear walls may be multiple panels wide.), no less than 8 inches from a top or bottom plate, or from any panel connection, and no more than 4 inches from the edge of an end panel. Raters can cut these holes themselves or can have someone on site cut them at their direction. A simple off-the-shelf hole-saw may be utilized. Plugs can be provided by the manufacturer if the specimen plug was damaged. See Figure 2 – *6" Insulation Density Sampling Holes for HERS Rater*, below. Density samples shall meet manufacturer's specifications for minimum required R-value. Note: There will be numerous access panels up to 12" square provided for Mechanical, Electrical, and Plumbing components. Since these holes are not randomly selected by the rater, they do not count as locations for any of the six density samples, but they can be used to visually inspect the insulation.



See Manufacturer's Allowable Hole Diagrams for additional information. Holes outside this scope to be approved by engineer of record for job specific requirements

1 1" Insulation Inspection Holes for HERS Rater



6" Insulation Density Sampling Holes for HERS Rater

2

Certificates

(a) All provisions of Residential Appendix RA2 shall be met. An Insulation Certificate of

Installation signed by the installer shall be provided that states the installation is consistent with the plans and specifications for which the building permit was issued. The certificate shall also state the installing company's name, manufacturer's name and material identification, and the installed R-value. The insulation installer shall also complete the applicable sections of the Certificate of Installation form and attach a product specification or data sheet for every insulation material used.

Certificates and Availability

(a) All provisions of Residential Appendix RA2 shall be met. The Insulation Certificate of Installation (CF2R-ENV-03), with insulation material labels or specification/data sheets attached, signed by the insulation installer, shall be available on the building site for each of the HERS rater's verification inspections. Note: The HERS rater cannot verify compliance credit without these completed forms.

Wall Insulation

(a) Connections of wall panels shall be sealed, caulked, foamed, or taped to provide a substantially air-tight envelope to the outdoors, attic, garage, and crawl space. Due to the extremely tight tolerances and overlapping joints, caulking and sealing is not required where the panels are joined using a ship lap joint, unless the project RDP directs otherwise. Sealing is required where the outer panel meets the top and bottom plates, where the inner panel meets the top plate and any other penetrations in the outer panel. All plumbing and wiring penetrations through the top and bottom of panels, as well as electrical boxes that penetrate the sheathing, shall be sealed. All gaps in the air barrier shall be caulked or sealed with minimally expansive foam or shall be taped.

(b) Bottom connections of wall panels shall be sealed to the ground subfloor or slab and sealed above the ground subfloor.

(c) Insulation shall uniformly fit across the plane of the wall, and required taping, caulking, or sealing of all joints and seams of panel joints shall be maintained to be considered the air barrier.

(d) Installer shall provide the bags-per-cubic-foot specifications and calculations and certify on the Certificate of Installation that the minimum weight-per-square-foot has been met.

(e) The panel manufacturer shall provide QII access holes as shown in the figure above.

Special Situations—Window and Door Headers

(a) All full-width window and door headers shall be insulated to a minimum of R-2 between the exterior face of the header and inside surface of the finish wall material when a header is required.

BAMCORE TER

BamCore Prime Wall System **TER No. 1507-03**

Issue Date: September 10, 2015
Updated: February 21, 2019
Subject to Renewal: January 1, 2020

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DIVISION: 06 00 00 – WOOD, PLASTICS AND COMPOSITES
Section: 06 17 00 – Shop-Fabricated Structural Wood
Section: 06 12 00 – Structural Panels
Section: 06 16 00 – Sheathing

1. Products Evaluated:

1.1. BamCore Prime Wall System (BamCore panelized Prime Wall system)

1.1.1. Prime Wall panel – Load bearing walls

1.2. For the most recent version of this Technical Evaluation Report (TER), visit drjengineering.org. For more detailed state professional engineering and code compliance legal requirements and references, visit drjengineering.org/statelaw. DrJ is fully compliant with all state professional engineering and code compliance laws.

1.3. This TER can be used to obtain product approval in any country that is an IAF MLA Signatory (all countries found here) and covered by an IAF MLA Evaluation per the Purpose of the MLA (as an example, see letter to ANSI from the Standards Council of Canada). Manufacturers can go to jurisdictions in the U.S., Canada and other IAF MLA Signatory Countries and have their products readily approved by authorities having jurisdiction using DrJ's ANSI accreditation.

1.4. Building code regulations require that evaluation reports are provided by an approved agency meeting specific requirements, such as those found in *IBC* Section 1703. Any agency accredited in accordance with ANSI ISO/IEC 17065 meets this requirement within ANSI's scope of accreditation. For a list of accredited agencies, visit ANSI's website. For more information, see drjcertification.org.

1.5. Requiring an evaluation report from a specific private company (i.e., ICC-ES, IAPMO, CCMC, DrJ, etc.) can be viewed as discriminatory and is a violation of international, federal, state, provincial and local anti-trust and free trade regulations.

1.6. DrJ's code compliance work:

1.6.1. Conforms to code language adopted into law by individual states and any relevant consensus based standard such as an ANSI or ASTM standard.

1.6.2. Complies with accepted engineering practice, all professional engineering laws and by providing an engineer's seal DrJ takes professional responsibility for its specified scope of work.

2. Applicable Codes and Standards:[1]

2.1. *2012, 2015* and *2018 International Building Code* (*IBC*)

2.2. *2012, 2015* and *2018 International Residential Code* (*IRC*)

2.3. *ASCE 7 – Minimum Design Loads for Buildings and Other Structures*

2.4. *ASTM C303 – Standard Test Method for Dimensions and Density of Preformed Block and Board-Type Insulation*

2.5. *ASTM C518 – Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*

2.6. *ASTM C1363 – Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus*

2.7. *ASTM C1699 – Standard Test Method for Moisture Retention Curves of Porous Building Materials Using Pressure Plates*

2.8. *ASTM C1794 – Standard Test Methods for Determination of the Water Absorption Coefficient by Partial Immersion*

2.9. *ASTM D198 – Standard Test Methods of Static Tests of Lumber in Structural Sizes*

2.10. *ASTM E72 – Standard Test Methods of Conducting Strength Tests of Panels for Building Construction*

2.11. *ASTM E84 – Standard Test Method for Surface Burning Characteristics of Building Materials*

2.12. *ASTM E90 – Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements*

2.13. *ASTM E96 – Standard Test Methods for Water Vapor Transmission of Materials*

2.14. *ASTM E119 – Standard Test Methods for Fire Tests of Building Construction and Materials*

2.15. *ASTM E283 – Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen*

2.16. *ASTM E2126 – Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings*

2.17. *AWC SDPWS – Wind and Seismic, Special Design Provisions for Wind and Seismic (SDPWS)*

2.18. *NIJ-STD-0108.01 – National Institute of Justice (NIJ) – Standard for Ballistic Resistant Protective Materials*

3. Performance Evaluation:

3.1. The BamCore Prime Wall system was evaluated to determine the following:

3.1.1. Structural performance under lateral load conditions for both wind and seismic loading for use with the *IBC* performance-based provisions, Section 2306.1 and 2306.3 for light-frame wood wall assemblies.

[1]Unless otherwise noted, all references in this code compliant technical evaluation report (TER) are from the 2018 version of the codes and the standards referenced therein, including, but not limited to, *ASCE 7*, *SDPWS* and *WFCM*. This product also complies with the 2000-2015 versions of the *IBC* and *IRC* and the standards referenced therein. As required by law, where this TER is not approved, the building official shall respond in writing, stating the reasons this TER was not approved. For variations in state and local codes, if any see Section 8.

3.1.1.1. Table 1 provides seismic design coefficients (SDC) that conform to the requirements in *ASCE/SEI 7-16* Section 12.2.1 and Table 12.2-1 for design of wall assemblies in buildings that require seismic design in accordance with *ASCE/SEI 7* (i.e., all seismic design categories).

3.1.1.2. The basis for equivalency testing is outlined in Section 12.2.1 of *ASCE/SEI 7*:

> Seismic force-resisting systems not contained in *ASCE/SEI 7* Table 12.2-1 are permitted provided analytical and test data are submitted to the authority having jurisdiction for approval that establish their dynamic characteristics and demonstrate their lateral force resistance and energy dissipation capacity to be equivalent to the structural systems listed in *ASCE/SEI 7* Table 12.2-1 for equivalent values of response modification coefficient, R, overstrength factor, Ω_o, and deflection amplification factor, C_d.

3.1.1.3. The SDC evaluation uses the approach found in documentation entitled "Equivalency Characteristics and Parameters for Proprietary Shearwalls Used in Wood Framed or Cold-formed Steel Construction"[2] and "Seismic Design Coefficients: How they are determined for light-frame components" [3] using code-defined accepted engineering procedures, experience and technical judgment.

3.1.2. Performance in accordance with *ASTM E84* for flame spread and smoke-developed index ratings in accordance with *IBC* Section 2603.5.4 and *IRC* Section R316.4.

3.1.3. Performance in fire-resistance rated assemblies in accordance with *ASTM E119*.

3.1.4. Performance for use as an air barrier assembly in accordance with the *IECC* Section C402.5.1.2.2.[4]

3.1.5. Compressive strength in accordance with *ASTM E72*.

3.1.6. Water vapor transmission performance in accordance with *ASTM E96*, *C1699*, and *C1794*.

3.1.7. Density in accordance with *ASTM C303*.

3.1.8. Sound transmission rating performance in accordance with *ASTM E90*.

3.1.9. Ballistics protection performance in accordance with *NIJ-STD-0108.01*.

3.2. Any code compliance issues not specifically addressed in this section are outside the scope of this TER.

4. Product Description and Materials:

Photo 1: House Being Built with BamCore Panelized Prime Wall System

[2] http://www.structuremag.org/wp-content/uploads/2014/08/C-StructuralPerformance-Nelson-Aug081.pdf
[3] http://www.sbcmag.info/article/2014/seismic-design-coefficients-how-they-are-determined-light-frame-components
[4] *2012 IECC* Section C402.4.1.2.2

4.1. The BamCore Prime Wall system is comprised of two laminated veneer bamboo (LVB) panels forming the interior and exterior faces of the wall assembly. The panels are fastened to wood plates or a metal track at the top and bottom of the wall assembly, as specified by approved structural construction documents. Contiguous panels are fastened to each other using one of the options listed in Section 4.1.4.3. Blocking between panels is added per specific job requirements. Specifically, the BamCore Prime Wall system consists of the following:

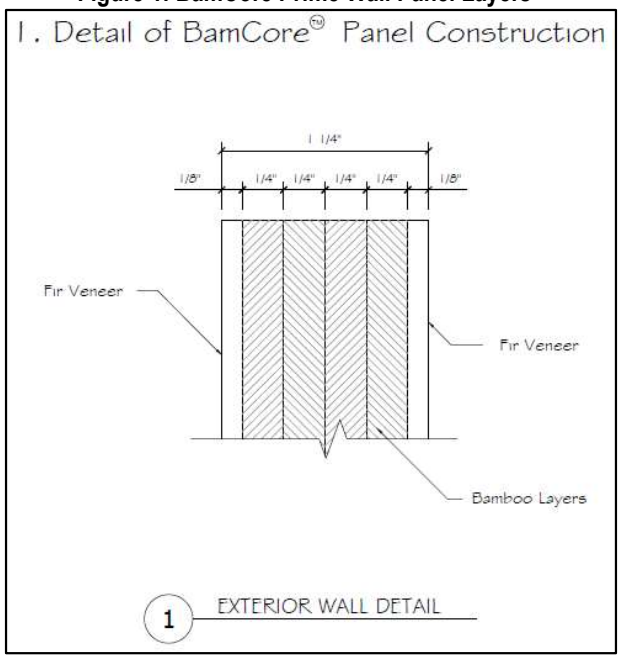
4.1.1. BamCore Prime Wall Panel Composition:

4.1.1.1. The panels consist of multiple LVB layers covered with nominal ⅛" (3.2 mm) Douglas Fir veneer on both faces.

4.1.1.2. The panels have a nominal thickness of 1-¼" (32 mm) (Figure 1).

4.1.1.3. The BamCore Prime Wall system may be designed with plate widths that allow outer wall dimensions from 5-½" (140 mm) to 13-¾" (349 mm).

Figure 1: BamCore Prime Wall Panel Layers



4.1.1.4. The finished wall assembly has a cavity that is slightly smaller (about 1/10th on an inch) than the width of the plate due to finishing of top and bottom panel edges.

4.1.1.5. Individual BamCore Prime Wall panels are manufactured with routed edges to form half lap joints at adjoining panel edges. The half lap joint is 1-1/2" (38 mm) wide; each panel has half their depth in the connection.

4.1.1.6. If steel top and bottom tracks are used, the panels are manufactured with top and bottom edges routed with grooves to allow for setting onto the 20-gauge steel tracks. The steel tracks are preformed with vertical legs which insert 1-1/2" (38 mm) into the top and bottom of the panels.

4.1.1.7. If steel splines are used to join the vertical panel edges, a kerf can be manufactured in the vertical edges of the panels to accept the 20-gauge x 3" (76 mm) wide G60 galvanized sheet metal splines.

4.1.2. Wood Top and Bottom Plates:

4.1.2.1. The wood top and bottom plates shall be minimum 2x6 No. 2 dimensional lumber with a minimum oven-dry specific gravity of 0.42 (SPF or denser material). Moisture content at the time of installation shall be 19% or less.

4.1.2.2. Both the interior and exterior panels are connected to the wood plates with 0.131" dia. x 3-¼" long (3.3 mm x 85 mm) nails spaced 3" (76 mm) on center. Install nails in the centerline of the 2x plates to maintain a minimum ¾" (19 mm) edge distance along the top and bottom of the panels (Figure 2).

Figure 2: BamCore Prime Wall Panel with Wood Top and Bottom Plate

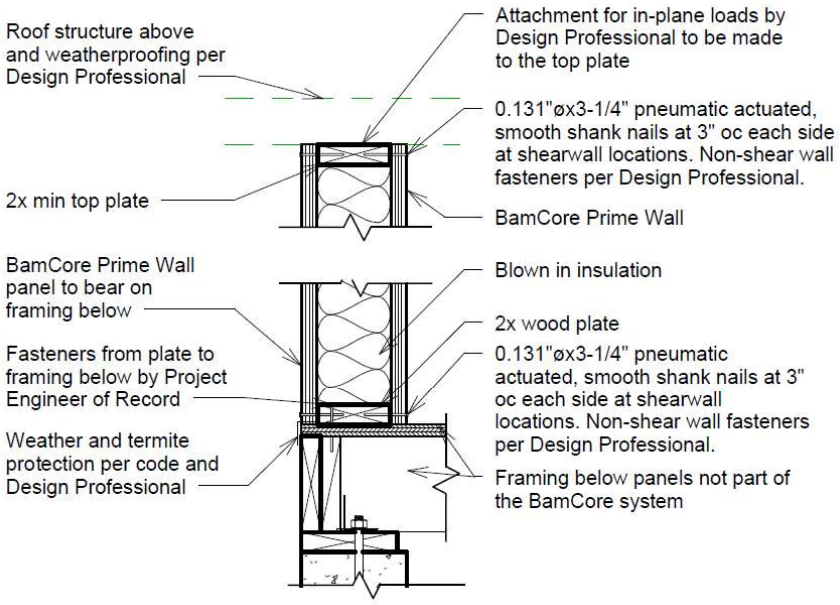
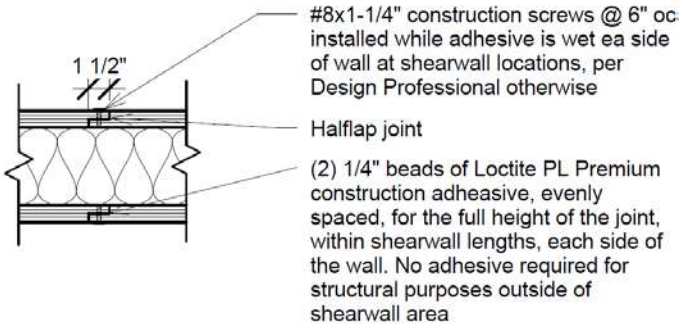


Figure 3: BamCore Prime Wall Panel Half Lap



4.1.3. Steel Top and Bottom Tracks

4.1.3.1. As an alternative to solid sawn wood top and bottom plates, the BamCore Prime Wall system is permitted to be constructed using steel top and bottom tracks.

4.1.3.2. The top and bottom tracks are 20-gauge (0.036") G60 galvanized metal, pre-formed with vertical legs which insert 1-½" (38 mm) into the top and bottom of the panels and provide the appropriate spacing for the panels.

4.1.3.3. The panels are manufactured with top and bottom edges routed with grooves to allow for setting onto 20-gauge steel tracks.

4.1.3.4. Steel tracks are available in widths that allow outer wall dimensions from 5-½" (140 mm) to 13-¾" (349 mm).

4.1.3.5. The BamCore Prime Wall panel shall be attached to the steel tracks with #10 x 1-¼" (32 mm), min. shank diameter - 0.184" (4.7 mm) flat head, square drive sheet metal screws.

4.1.4. Fastening:

4.1.4.1. Contiguous panels within a shear wall shall be connected together at vertical joints with a half lap joint (Figure 3).

4.1.4.2. The half lap joint is 1-1/2" (38 mm) wide; each panel has half their depth in the connection.

4.1.4.2.1. For shear walls with solid sawn wood plates, the half lap joint shall be connected with two (2) ¼" (6.3 mm) continuous beads of Loctite PL Premium Construction Adhesive along the full length of the joint and, #8 x 1-¼" (32 mm) screws spaced 6" o.c. (152 mm) to be placed before the adhesive sets.

4.1.4.2.2. For shear walls with steel tracks, the half lap joint shall be connected with #10 x 1-¼" (32 mm) flat head standard wood screws at 8" o.c. (203 mm).

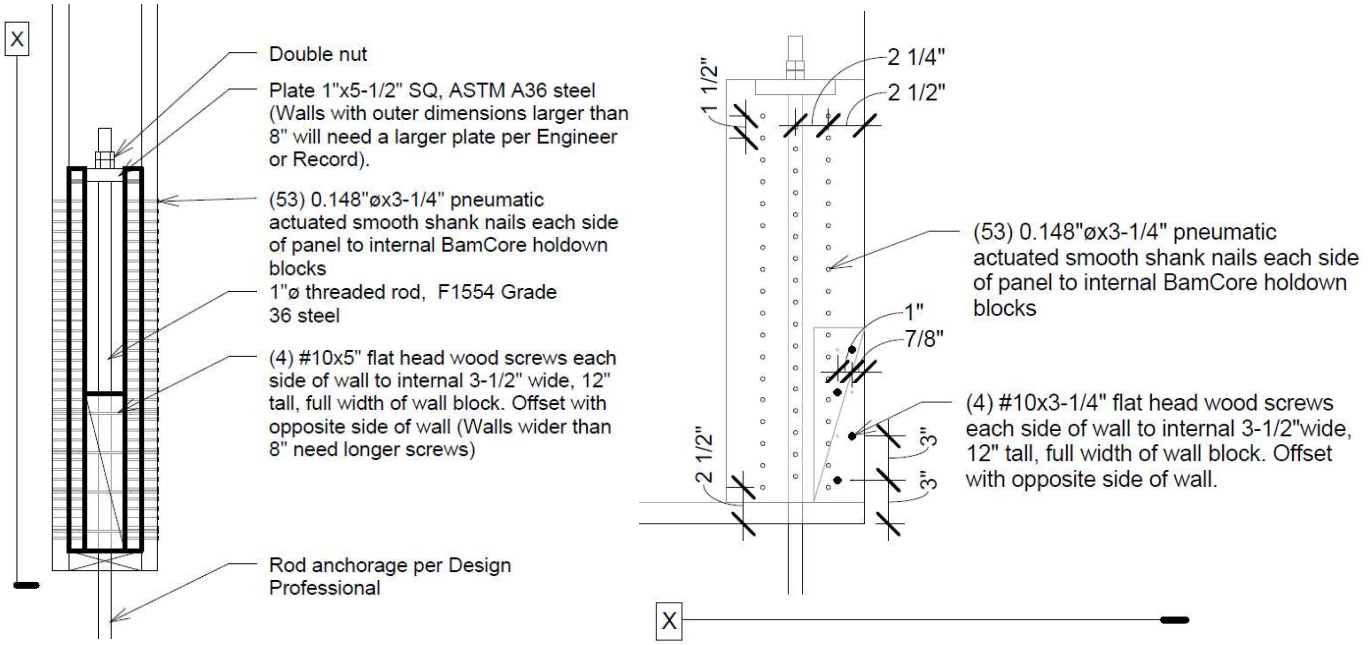
4.1.4.3. Contiguous panels are permitted to be connected using a 3" (76 mm) wide, 20-gauge sheet metal spline for connections not located in a shear wall.

4.1.4.3.1. For the spline connection, #10 x 1-¼" (32 mm) flat head, square drive sheet metal screws at 8" o.c. (203 mm).

4.1.5. Hold-Downs:

4.1.5.1. For shear wall applications with solid sawn wood plates, hold-downs are composed of a partial height BamCore block nailed to the inside of each panel. A metal plate sits on top of the blocks and is attached the foundation/framing below using a threaded rod. See Figure 4 for attachment requirements.

Figure 4: Prime Panel Hold-down for Wood Plate System



4.1.5.2. For shear wall applications with steel tracks, hold-down blocks are installed at the top corners of each panel assembly and held down with threaded rods as required by the design.

4.1.5.2.1. The hold-down block is 12" (305 mm) long with a steel plate on top and a threaded rod centered on the block and plate connecting it to the foundation below.

4.1.5.2.2. The panels are routed ⅝" (15.6 mm) on the inside face of each panel with the hold-down block set into the routes so that it has direct bearing.

4.1.5.2.3. #8 x 3" (76 mm) deck screw, coarse, square drive – used to attach panels to hold-down blocks.

4.1.6. Blocking:

4.1.6.1. Vertical panel blocking shall be installed in the cavity between the two runs of panels and fastened to the BamCore Prime Wall panels using minimum #10 by 3-¾" (95 mm) wood screws at 4" o.c. (102 mm) maximum. Blocking height and spacing depend on specific job requirements as specified in the construction documents.

4.1.6.2. Blocking around window/door openings are to be fastened using minimum #10 by 3-¾" (95 mm) wood screws at 8" o.c. (203 mm) maximum.

4.2. BamCore Prime Wall systems are prefabricated to a job-specific engineered plan and delivered to the jobsite with materials as specified in BamCore-to-client contracts. The BamCore Prime Wall system is not installed by BamCore LLC.

5. Applications:

5.1. Structural Applications

5.1.1. Where the application exceeds the limitations set forth herein, design shall be permitted in accordance with accepted engineering procedures, experience and technical judgment.

5.2. Shear Wall Design

5.2.1. BamCore Prime Wall panels may be designed as shear walls to resist lateral loads using the ASD allowable unit shear capacities given in Table 1.

5.2.2. The maximum aspect ratio for full height BamCore Prime Panel shear walls shall be 1:1.

5.2.3. Seismic design for BamCore Prime Wall panels shall not be required in buildings exempt from seismic design in accordance with *IBC* Section 1613.

5.2.4. BamCore Prime Wall panel shear walls that require seismic design in accordance with *IBC* Section 1613 shall use the seismic allowable unit shear capacities set forth in Table 1.

5.2.4.1. The response modification coefficient, R, system overstrength factor, Ω_0, and deflection amplification factor, C_d, indicated in Table 1 shall be used to determine the base shear, element design forces, and design story drift in accordance with *ASCE/SEI 7* Chapter 12 and Section 14.5.

Table 1: Wind or Seismic Allowable Unit Shear Capacity & Seismic Design Coefficients for the BamCore Prime Wall System[1,2]											
Seismic Force-Resisting System	Top and Bottom Plate Material	Wind or Seismic Allowable Unit Shear Capacity[3] (plf)(kN/m)	Apparent Shear Stiffness, G_a (kips/in.)	Response Modification Factor, R[4]	System Overstrength Factor, Ω_0[5]	Deflection Amplification Coefficient, C_d[6]	Structural System Limitations & Building Height (ft.) Limit[8]				
							Seismic Design Category				
							B	C	D	E	F
BamCore Prime Wall System	2x Lumber	1,100 (16.1)	18.0	2.0	2.5	2.0	NL	NL	65	65	65
BamCore Prime Wall System with ACQ Pressure Treatment	2x Lumber	705 (10.3)	15.5	2.0	2.5	2.0	NL	NL	65	65	65
BamCore Prime Wall System	Steel Track	555 (8.1)	10.5	3.4	3	4	NL	NL	65	65	65
BamCore Prime Wall System with ACQ Pressure Treatment	Steel Track	360 (5.3)	9.0	3.4	3	4	NL	NL	65	65	65

For SI: 1 plf = 0.0145 kN/m
1. BamCore Prime Wall System attached in accordance with Section 4 and Section 6.
2. All seismic design parameters follow the equivalency as defined in Section 3 of this TER.
3. The allowable unit shear capacity is calculated using a factor of safety of 2.5 per *ASCE/SEI 7*.
4. Response modification coefficient, R, for use throughout *ASCE/SEI 7*. Note: R reduces forces to a strength level, not an allowable stress level.
5. The tabulated value of the overstrength factor, Ω_0, is permitted to be reduced by subtracting one-half (0.5) for structures with flexible diaphragms.
6. Deflection amplification factor, C_d, for use with *ASCE/SEI 7* Section 12.8.6, 12.8.7, and 12.9.2.
7. Panel shear wall deflection shall be calculated as:

$$\delta_{sw} = (vh / 1000G_a) + (h\Delta_a / b)$$

Where:

v = induced unit shear, lbs/ft
h = shear wall height, ft.
G_a = apparent shear wall stiffness, 10.5
Δ_a = total vertical elongation of the wall anchorage system at the induced unit shear in the shear wall, in.
b = shear wall length, ft.

8. NL = Not Limited. Heights are measured from the base of the structure as defined in *ASCE 7/SEI* Section 11.2.

5.3. Axial Compressive Strength

5.3.1. BamCore Prime Wall systems were tested in accordance with *ASTM E72*, Section 9, for compressive strength.

Table 2: BamCore Prime Wall Allowable Compressive Strength[1]			
Wall Height	Minimum Nominal Thickness of Wall System (in.)(mm)	Allowable Compressive Strength (plf)(kN/m)	Allowable Compressive Strength (plf)(kN/m) with ACQ Pressure Treatment
8'	8" (203)	3730 (54.4)	2425 (35.4)
9'		3490 (50.9)	2270 (33.1)
10'		3245 (47.4)	2110 (30.8)

For SI: 1 plf = 0.0145 kN/m, 1 inch = 25.4 mm
1. Testing per *ASTM E72*.

5.4. BamCore Prime Wall system headers - In-Plane Bending Strength

5.4.1. BamCore Prime Wall panels may be designed as wall headers to carry gravity loads using the reference design values given in Table 3. See Figure 5 for details of header construction.

5.4.2. Design of BamCore Prime Wall headers is governed by the applicable code and the provisions for Structural Composite Lumber (SCL) in *NDS*.

5.4.3. Unless otherwise noted, adjustment of the reference design values for duration of load shall be in accordance with the applicable code.

Table 1: Reference Design Values for BamCore Prime Wall System (Allowable Stress Design)[1,2,3]						
Bending, F_b (psi) (Mpa)	Compression, F_c (psi) (Mpa)		Horizontal Shear, F_v (psi) (Mpa)	Modulus of Elasticity, E (psi) (Mpa)	Modulus of Rigidity, G (psi) (Mpa)	Modulus of Elasticity for Beam Stability, E_{min} (psi) (Mpa)
Beam[4, 5, 6]	Parallel-to-Grain	Perpendicular-to-Grain[7]	Beam	True[4]	Beam	
2,400 (16.55)	2625 (18.10)	660 (4.55)	270 (1.86)	2,600,000 (17,931)	75,300 (519)	730,000 (5,034)

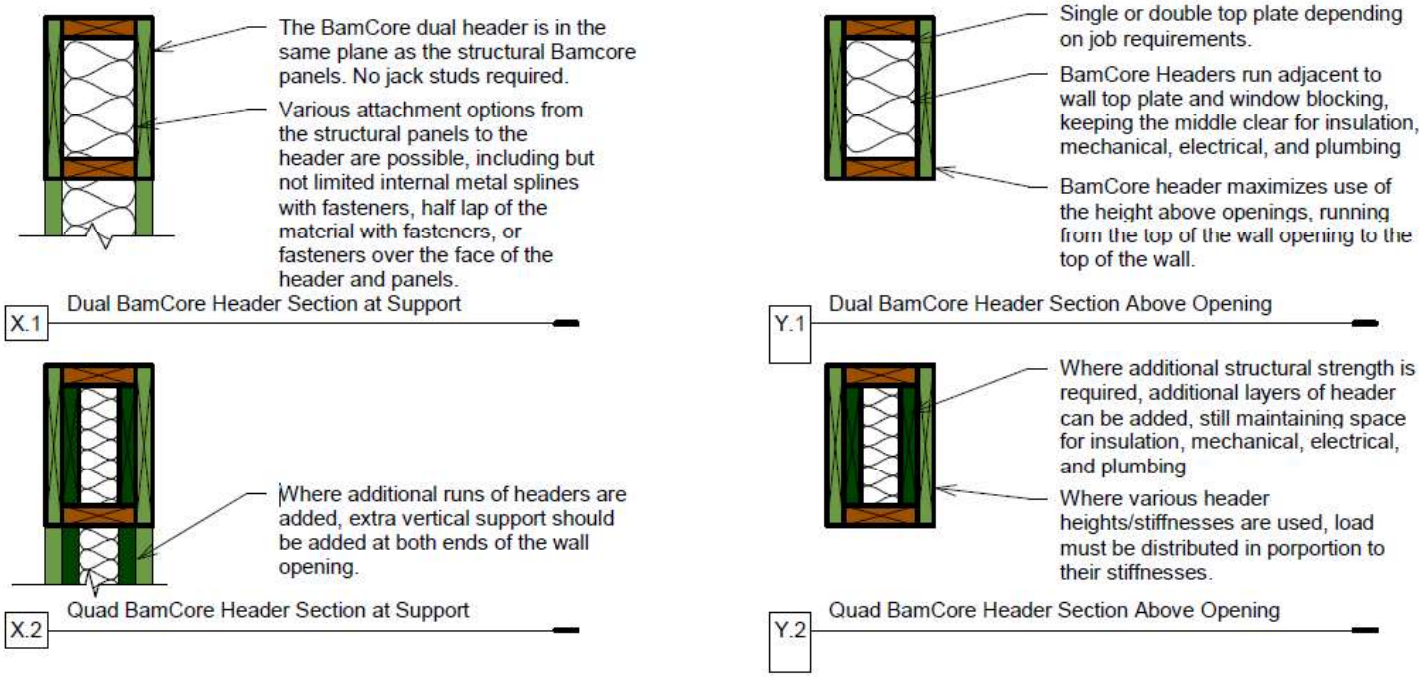
1 psi = 0.00689 MPa or 1 MPa = 145 psi.

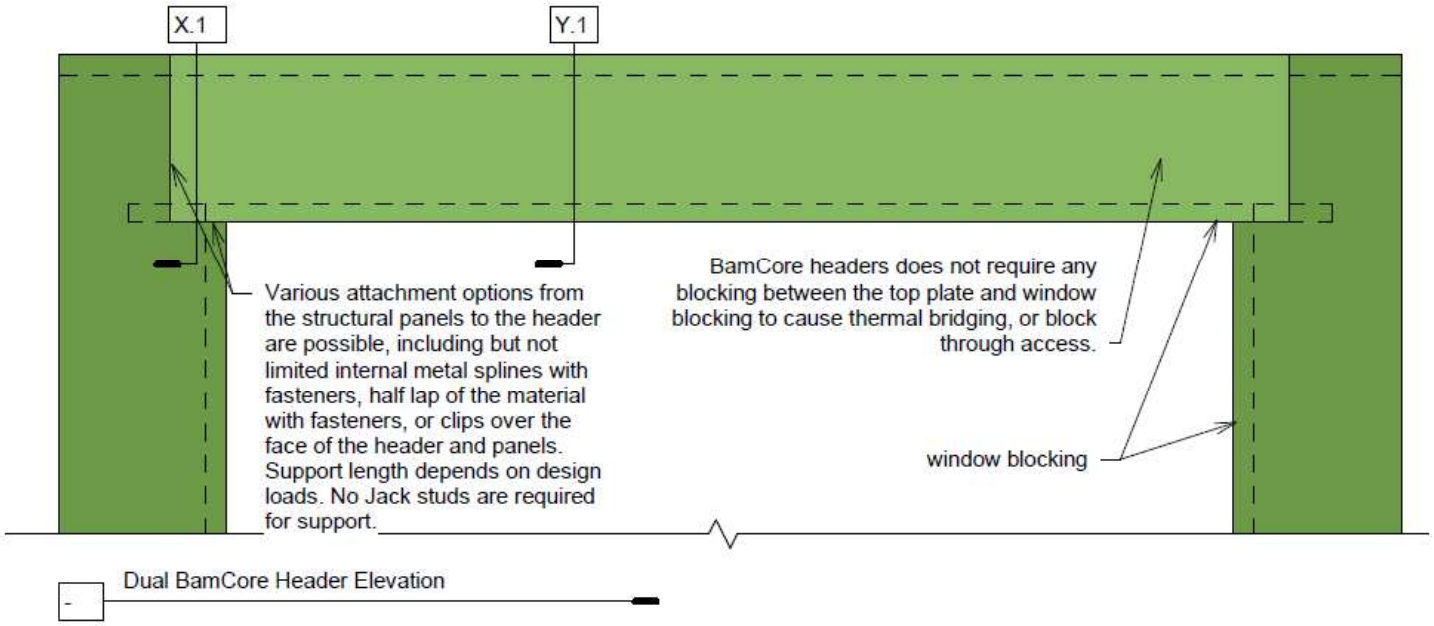
1. The reference design values in this table are applicable for the product used in dry, well-ventilated interior applications, in which the equivalent moisture content of sawn lumber is less than 16%. See Section 9.4.4 of this TER.
2. The reference design values in this table are for normal load duration. Loads of other duration shall be adjusted in accordance with the applicable code. Duration of load adjustments shall not be applied to $F_{c\perp}$ and E.
3. Reference design values (except for compression parallel-to-grain) are for the BamCore Prime Wall with vertical load applied along the panel edge with the strength axis (i.e., long direction of the panel) oriented parallel to the span.
4. The calculated deflection of flexural members must account for combined bending and shear deflection. For uniformly loaded simple span beams, the deflection is calculated as follows:

   $\Delta = [5WL^4/(32Ebh^3)] + [63WL^2/(20Ebh)]$

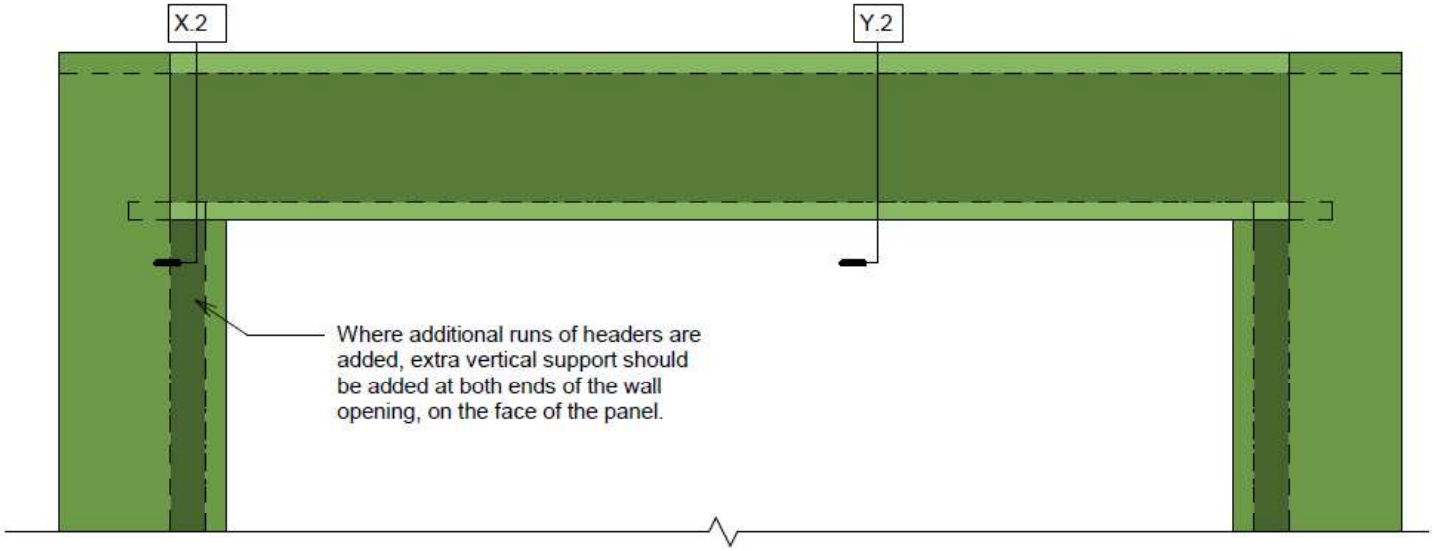
   where: Δ = deflection in inches (mm)
   W = uniform load in lbs./in. (N/mm)
   L = span in inches (mm)
   E = modulus of elasticity in psi (MPa)
   b = width of beam in inches (mm)
   h = depth of beam in inches (mm)
5. The bending values in these tables are based on a reference depth of 12" (305 mm). For other depths, the bending value shall be adjusted by a size factor adjustment of $(12/d)^{0.98}$, where d is measured in inches with a minimum depth of 12" (178 mm). Bending values are valid for members 1.25" in thickness and a unit volume not to exceed 10,752 sq.in based on the member length times the member depth.
6. When structural members qualify as repetitive members in accordance with the applicable code, a 4% increase is permitted.
7. The minimum bearing length shall be checked based on Compression Perpendicular-to-Grain. Where needed, additional bearing blocking may be added.

Figure 5: Details for BamCore Prime Wall Header Construction





Dual BamCore Header Elevation



Quad BamCore Header Elevation

5.5. Transverse Strength

5.5.1. BamCore Prime Walls were tested in accordance with *ASTM E72*, Section 12, for transverse load.

5.5.2. BamCore Prime Walls were evaluated to assess the strength and deflection of the panels when subjected to transverse wind loading.

Table 4: Deflection Performance of BamCore Prime Walls

Application	Blocking	Deflection Limit	Wall Height, H (ft)	Allowable Transverse Load (psf)	Allowable Transverse Load with ACQ Pressure Treatment (psf)	Max. Wind speed (V_{ult})	Max. Wind speed (V_{ult}) with ACQ Pressure Treatment
Exterior Walls – wind loads with flexible finishes	4' o.c. Blocking. Blocking length 85% of full height[1]	H/120	8	78.1 (3.7)	68.8 (3.2)	180	180
			9	54.9 (2.6)	48.3 (2.3)	180	180
			10	40.0 (1.9)	35.2 (1.7)	180	180
Exterior Walls – wind loads with flexible finishes		H/180	8	78.1 (3.7)	68.8 (3.2)	180	180
			9	54.9 (2.6)	48.3 (2.3)	180	180
			10	40.0 (1.9)	35.2 (1.7)	180	180
Exterior Walls – wind loads with other brittle finishes		H/240	8	62.5 (3.0)	55.0 (2.6)	180	180
			9	43.9 (2.1)	38.6 (1.8)	180	180
			10	32.0 (1.5)	28.2 (1.4)	180	170
Exterior Walls – wind loads with plaster or stucco finish		H/360	8	49.0 (2.3)	43.1 (2.1)	180	180
			9	34.4 (1.6)	30.3 (1.5)	180	170
			10	25.1 (1.2)	22.1 (1.1)	160	150
Exterior Walls – wind loads with flexible finishes	8' o.c. Blocking. Blocking length 50% of full height[2]	H/120	8	38.5 (1.8)	33.9 (1.6)	180	180
			9	27.0 (1.3)	23.8 (1.1)	170	160
			10	19.7 (0.9)	17.3 (0.8)	150	140
Exterior Walls – wind loads with other brittle finishes		H/180	8	20.3 (1.0)	17.9 (0.9)	150	140
			9	14.3 (0.7)	12.6 (0.6)	130	120
			10	10.4 (0.5)	N/A	110	N/A

1 Pound per square foot [psf] = 0.047 880 26 kN/m²

1. Based on *ASTM E72*, Section 12 testing with 8' x 10' panels. Blocking (85% full height) installed at panel edges and mid-panel at 4' o.c. Allowable transverse load is based the lesser of strength and deflection checks. Deflection controls in all cases. Deflection is calculated based on 0.7 times components and cladding loads per *IRC* Table R301.2(2) for wall zone 5, an effective area of 20 sq.ft., Exposure B and a mean roof height of 30 feet.
2. Based on *ASTM E72*, Section 12 testing with 8' x 10' panels. Blocking (50% full height) installed at mid-height of panel edges at 8' o.c. Allowable transverse load is based the lesser of strength and deflection checks. Deflection controls in all cases. Deflection is calculated based on 0.7 times components and cladding loads per *IRC* Table R301.2(2) for wall zone 5, an effective area of 50 sq.ft., Exposure B and a mean roof height of 30 feet.

5.6. Fire Resistance

5.6.1. Surface Burn Characteristics

Table 5: Fire Performance of BamCore Prime Walls

	Flame Spread	Smoke Developed
BamCore Prime Wall[1]	40	100

1. Tested in accordance with *ASTM E84*. Flame spread, and smoke developed numbers are shown for comparison purposes only and are not intended to represent the performance of BamCore Prime Wall panels and related components under actual fire conditions.

5.6.2. Fire-Resistance Rated Wall Assemblies

Table 6: Fire-Resistance Rating of BamCore Prime Walls		
	Layers of Type X Gypsum on Each Side of Assembly	**Fire-Resistance Rating (minutes)**
BamCore Prime Wall[1]	1	60
BamCore Prime Wall[1]	2	120

1. Tested in accordance with *ASTM E119* with one layer of Type X gypsum installed on each side of assembly. Construction shall be in accordance with Section 5.6.3.
2. Tested according to ASTM E119 with two layers of Type X gypsum installed on each side of assembly. Construction shall be in accordance with Section 5.6.4

5.6.3. One-hour rated assembly

5.6.3.1. BamCore Prime Wall assemblies were tested per *ASTM E119* and have a 1-hour fire resistance rating when constructed as follows:

5.6.3.1.1. BamCore Prime Walls are assembled using the steel top and bottom track method and are fastened with 1-1/8" (29 mm) (self-tapping screws at 8" o.c. (203 mm). Minimum cavity depth of 5-½" (140 mm) is required.

5.6.3.1.2. Panel joints are constructed using the metal splines and are fastened with 1-1/8" (29 mm) self-tapping screws at 8" o.c. (203 mm).

5.6.3.1.3. A panel stiffener (minimum 1-¼" x 5-½" x 5') (29 mm x 140 mm x 1,524 mm) is installed vertically at mid-height within 5' (1524 mm) of the end of the wall and every 10' o.c. (3048 mm) along the length of the wall. The stiffener is attached with minimum #8 x 3" (76 mm) screws.

5.6.3.1.4. A bead of fire sealant (3M Fire Barrier Sealant, 3-hr or equivalent) is applied to all joints and voids in the panel surfaces

5.6.3.1.5. Cellulose insulation is installed in the cavity at approximately 3 lb. per ft^3.

5.6.3.1.6. One layer of 5/8" (15.9 mm) Type X gypsum is installed on each face of the wall assembly with 1-5/8" (41 mm) drywall screws fastened 12" o.c. (305 mm). All joints are taped and covered with 2 layers of joint compound. Exposed screw heads are also covered with 2 coats of joint compound. Gypsum joints on one side of the wall are staggered from the joints on the opposite side by 24" (610 mm).

5.6.4. Two-hour rated assembly

5.6.4.1. BamCore Prime wall assemblies were tested per *ASTM E119* and have a 2-hour fire resistance rating when constructed as follows:

5.6.4.1.1. BamCore Prime Walls are assembled using the steel top and bottom track method and are fastened with 1-1/8" (29 mm) self-tapping screws at 8" o.c. (203 mm). Minimum cavity depth of 5-½" (140 mm) is required.

5.6.4.1.2. Panel joints are constructed using the metal splines and are fastened with 1-1/8" (29 mm) self-tapping screws at 8" o.c. (203 mm).

5.6.4.1.3. A panel stiffener (minimum 1-¼" x 5-½" x 5') (29 mm x 140 mm x 1,524 mm) is installed vertically at mid-height within 5' (1524 mm) of the end of the wall and every 10' o.c. (3048 mm) along the length of the wall. The stiffener is attached with minimum #8 x 3" (76 mm) screws.

5.6.4.1.4. A bead of fire sealant (3M Fire Barrier Sealant, 3-hr or equivalent) is applied to all joints and voids in the panel surfaces

5.6.4.1.5. Cellulose insulation is installed in the cavity at approximately 3 lb. per ft^3.

5.6.4.1.6. Two layers of 5/8" (15.9 mm) Type X gypsum are installed on each face of the wall assembly. The base layer is attached with 1-5/8" (41 mm) drywall screws fastened 12" o.c. (305 mm). The face layer is attached with 2-½" (64 mm) screws at 8" o.c. (203 mm).

5.6.4.1.6.1. All joints in the face layer are taped and covered with 2 layers of joint compound. Exposed screw heads are also covered with 2 coats of joint compound. Gypsum joints on one side of the wall are staggered from the joints on the opposite side by 24" (610 mm).

5.7. Air Barrier

5.7.1. BamCore Prime Walls meet the requirements of *IECC* Section C402.5 for use in an air barrier assembly when installed in accordance with the manufacturer's installation instructions and this TER.

5.7.1.1. The tested air barrier assembly consists of BamCore Prime Walls nominally 8" (203 mm) thick constructed with metal splines as described in Section 4.1. The cavity of the wall is filled with blown–in cellulose fiber insulation at 3.5 lb/ft^3 density.

Table 7: BamCore Prime Wall Panels Air Barrier Properties by Assembly[1]

	Infiltration Rate
BamCore Prime Wall Panel	< 0.2 (L/s.m^2)[2]

1. Tested in accordance with *ASTM E283 and a 6.27 psf pressure differential*. Cavity filled with blown cellulose insulation. Joints between prime panels and any overdriven nails caulked with silicone.
2. Liter per second per square meter.

5.8. Water Vapor Transmission

5.8.1. BamCore Prime Walls have the following water vapor transmission values:

Table 8: Water Vapor Permeance of BamCore Prime Wall Panels

	Permeance (perms)[1] (grains/hr/in/Hg/ft^2)	Water Absorption Coefficient[2] ((kg/m^2·h$^{1/2}$))	Equilibrium Moisture Content at 100% relative humidity[3] (kg/kg)
BamCore Prime Wall Panel	7.9	0.190	0.55

1. Tested in accordance with *ASTM E96* using the "wet cup" method.
2. Tested in accordance with *ASTM C1794*.
3. Tested in accordance with *ASTM 1699*.

5.9. Density

5.9.1. BamCore Prime Walls have the following density value:

Table 9: Density of BamCore Prime Walls

	Average Density
BamCore Prime Wall[1]	36.7 lb$_m$/ft^3 (587. kg/m^3)

1. Tested in accordance with *ASTM C303*.

5.10. Sound Transmission

5.10.1. BamCore Prime Walls have the following sound transmission ratings:

Table 10: BamCore Prime Wall Sound Transmission Ratings[1,2]		
Assembly	**Sound Transmission Class (STC)**	**Outside Inside Transmission Class (OITC)**
Single Layer 5/8" Type X on One Side[3]	46	42
Single Layer 5/8" Type X on Both Sides[4]	51	46
Double Layer 5/8" Type X on Both Sides[5]	55	48

1. Tested in accordance with *ASTM E90*.
2. Framing details: One-half height blocking installed at 8' (203 mm) o.c along the length of the wall attached with #10 x 3-3/4" (95 mm) wood screws at 4" o.c. (102 mm). Half lap splice joints at panel edges attached with 0.113" x 2" (51 mm) ring shank nails at 3" o.c. (76 mm). 5/8" (15.9 mm) Type X gypsum applied to both faces at 16" o.c. (406 mm) horizontally and 12" o.c. (305 mm) vertically with #6 Type W drywall screws. Gypsum seam caulked with silicone. Wall cavity filled with blown cellulose insulation.
3. Framing factor of 6.65%.
4. Framing factor of 3.91%.
5. Framing factor of 3.91%.

5.11. Thermal Resistance (R-Value)

5.11.1. BamCore Prime Walls have the following R-Values:

Table 11: BamCore Prime Wall R-Values			
BamCore Prime Wall Component R-Values[1] and U-factors			
Nominal Thickness	**Thermal R-Value[2]**	**Thermal U-factor**	
1.25"	1.6	0.625	
BamCore Prime Wall Assembly R-Values[3] and U-factors			
Assembly	**Thermal R-Value**	**Thermal U-factor (50°F to 100°F)**	**Thermal U-factor (0°F to 70°F)**
BamCore Prime Wall with Single Layer 5/8" (15.9 mm) Type X on One Side[4]	20.3	0.047	0.037
BamCore Prime Wall with Single Layer 5/8" (15.9 mm) Type X on Both Sides[5]	22.3	0.043	N/A

1. Thermal values are determined using the *ASTM C518* test method at 75°F mean temperature and 50°F temperature differential.
2. R-Value given is for one panel only.
3. Thermal values are determined using the *ASTM C1363* test method at 75°F mean temperature and 50°F temperature differential. Cavity of wall filled with 5-½" (140 mm) dry cellulose blown-in insulation at 3.5# density. Seams of Prime panels and Gypsum filled with silicone caulking.
4. Framing factor of 6.65%, representative of an exterior wall configuration).
5. Framing factor of 3.91%, representative of a common wall configuration).

5.12. Ballistics

5.12.1. BamCore Prime Walls satisfied the ballistic resistance requirements of National Institute of Justice (NIJ) Standard-0108.01 – Level I, see Figure 6.

5.12.1.1. Level I protection can resist .38 Special and .22 long rifle hyper velocity rounds when fired 16' or more from the installed wall and provides protection against many types of handguns.

Figure 6: BamCore Prime Wall Ballistic Test

6. Installation:

6.1. General

6.1.1. Installation shall comply with the manufacturer's installation instructions, approved construction documents, and this TER. In the event of a conflict between the manufacturer's installation instructions, approved construction documents, and this TER, the more restrictive instructions shall govern.

6.1.2. The BamCore Prime Wall panels must be stored and handled to protect panels from damage in storage, during shipment, and on the job site. If panels must be stored outside, stack them on a level platform supported by at least three 4x4s to keep them off the ground. Place one 4x4 in the center and the other two 12" (305 mm) to 16" (406 mm) from the ends. Never leave the platform in direct contact with the ground. Cover the stack loosely with plastic sheets or tarps. Anchor the covering at the top of the stack, but keep it open and away from the sides and bottom to ensure good ventilation. Tight coverings prevent air circulation and when exposed to sunlight, may promote mold or mildew. Please refer to the APA EWS Technical Note E705 – March 2005, "Proper Storage and Handling of I-Joists and LVL" and the APA Builder Tips on "Storage and Handling of APA Trademarked Panels" for additional recommendations.

6.1.3. BamCore Prime Walls shall be designed for dry use and shall be adequately protected from moisture and pests.

6.2. BamCore Prime Walls shall be installed in accordance with the construction documents, the installation instructions provided with the shipment of panels, and this TER. In the event of a conflict between the manufacturer's installation instructions, approved construction documents by a registered design professional (RDP), and this TER, the more restrictive shall govern.

6.2.1. Generic details provided by BamCore shall be evaluated and revised by a RDP for applicability to a specific building.

6.2.2. Support for BamCore Prime Walls (e.g., foundation walls, footings, etc.) shall be designed by a RDP.

6.3. Support for BamCore Prime Walls must be flat, level, free of debris, and match the dimensions provided by a RDP.

6.4. BamCore Prime Walls are installed and aligned in accordance with the plans designed and submitted to the building official per Section 9.

6.5. All panels are stamped with sequencing identification to correspond to the construction documents for easy placement in the correct location.

6.6. Step-by-Step Installation Instructions

6.6.1. Layout the bottom plate/track as shown on the construction documents. Attach to the structure above and below per approved construction documents.

6.6.2. Install panels for the exterior side of the wall starting at a corner.

6.6.3. Place adjoining panels per the numbered sequencing on the construction documents by placing each panel on/next to the plate. Fasten per Section 4.1 and approved construction documents. Continue until all exterior panels are set.

6.6.4. Repeat the steps above for the panels on the interior side of the exterior walls. Refer to construction documents to determine placement of additional blocking for deflection criteria to be met.

6.6.5. Add panel blocking around each window and door to connect the panels on the interior and exterior sides of the exterior walls together.

6.6.6. The top plate can either be set on blocking or clamped in place while fastening it to the panel. Fasten per Section 4.1 and approved construction documents.

6.6.7. Interior load bearing walls are installed in the same manner.

6.6.8. For more details on the installation of BamCore Prime Wall assemblies and subsequent installation of other trades within the assemblies, see the BamCore website.

7. Test and Engineering Substantiating Data:

7.1. Test reports and data supporting the following material and structural properties:

7.1.1. Shear wall performance in accordance with *ASTM E72* and *ASTM E2126* by the Composite Materials and Engineering Center of Washington State University.

7.1.2. Transverse and axial load performance in accordance with *ASTM E72*, Sections 9 and 12, by Intertek/ATI.

7.1.3. Thermal properties in accordance with *ASTM C518* by QAI Laboratories.

7.1.4. Thermal properties in accordance with *ASTM C1363* by Intertek.

7.1.5. Flame spread and smoke density in accordance with *ASTM E84* by QAI Laboratories.

7.1.6. Fire-resistant assembly rating in accordance with *ASTM E119* by Western Fire Center, Inc.

7.1.7. Water vapor transmission in accordance with *ASTM E96* by Radco, Inc., and *ASTM C1699*, *C1794* by R&D Services.

7.1.8. Density value in accordance with *ASTM C303* by R&D Services.

7.1.9. Sound transmission in accordance with *ASTM E90* by Intertek.

7.1.10. Ballistics testing in accordance with NIJ 0108.01 by Oregon Ballistic Laboratories.

7.1.11. Air Barrier Assembly testing in accordance with *ASTM E283* by Intertek and National Certified Testing Laboratories.

7.2. The product(s) evaluated by this TER fall within the scope of one or more of the model, state or local building codes for building construction. The testing and/or substantiating data used in this TER is limited to buildings, structures, building elements, construction materials and civil engineering related specifically to buildings.

7.3. The provisions of model, state or local building codes for building construction do not intend to prevent the installation of any material or to prohibit any design or method of construction. Alternatives shall use consensus standards, performance-based design methods or other engineering mechanics based means of compliance. This TER assesses compliance with defined standards, accepted engineering analysis, performance-based design methods, etc. in the context of the pertinent building code requirements.

7.4. Some information contained herein is the result of testing and/or data analysis by other sources, which DrJ relies on to be accurate, as it undertakes its engineering analysis.

7.5. DrJ has reviewed and found the data provided by other professional sources are credible. The information in this TER conforms with DrJ's procedure for acceptance of data from approved sources.

7.6. DrJ's responsibility for data provided by approved sources conforms with *IBC* Section 1703 and any relevant professional engineering law.

7.7. Where appropriate, DrJ's analysis is based on design values that have been codified into law through codes and standards (e.g., *IRC*, *WFCM*, *IBC*, *SDPWS, NDS, ACI, AISI, PS-20, PS-2*, etc.). This includes review of code provisions and any related test data that aids in comparative analysis or provides support for equivalency to an intended end-use application. Where the accuracy of design values provided herein is reliant upon the published properties of commodity materials (e.g., lumber, steel, concrete, etc.), DrJ relies upon grade/properties provided by the raw material supplier to be accurate and conforming to the mechanical properties defined in the relevant material standard.

8. Findings:

8.1. BamCore Prime Wall System as described in this TER comply with, or are suitable alternatives to, the applicable building codes listed in Section 2 within the scope of this TER and are subject to the conditions listed in Section 9.

8.2. *IBC* Section 104.11 (*IRC* Section R104.11 and *IFC* Section 104.9 are similar) states:

> **104.11 Alternative materials, design and methods of construction and equipment.** The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been *approved*. An alternative material, design or method of construction shall be *approved* where the *building official* finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, not less than the equivalent of that prescribed in this code. … Where the alternative material, design or method of construction is not *approved*, the *building official* shall respond in writing, stating the reasons the alternative was not *approved*.

8.3. This product has been evaluated in the context of the codes listed in Section 2, and is compliant with all known state and local building codes. Where there are known variations in state or local codes that are applicable to this evaluation, they are listed here:

8.3.1. No known variations

8.4. This TER uses professional engineering law, the building code, ANSI/ASTM consensus standards and generally accepted engineering practice as its criteria for all testing and engineering analysis. DrJ's professional engineering work falls under the jurisdiction of each state Board of Professional Engineers, when signed and sealed.

9. Conditions of Use:

9.1. Where required by the authority having jurisdiction (AHJ) in which the project is to be constructed, this TER and the installation instructions shall be submitted at the time of permit application.

9.2. Any generally accepted engineering calculations needed to show compliance with this TER shall be submitted to the code official for review and approval.

9.3. Design loads shall be determined in accordance with the building code adopted by the jurisdiction in which the project is to be constructed and/or by the Building Designer (e.g., Owner, RDP, etc.).

9.4. BamCore Prime Walls must be designed, manufactured, labelled and installed in accordance with this TER and the applicable building code.

9.4.1. All connections shall be in accordance with this TER, approved construction documents (by a registered design professional), and the applicable building code, based on individual job requirements.

9.4.2. Design calculations and details shall be furnished to the code official verifying that the material is used in compliance with this TER. The calculations must be prepared by a registered design professional where required by the statutes of the jurisdiction in which the project is to be constructed.

9.4.3. The design values shall not exceed those set forth in this report as modified by all applicable table notes.

9.4.4. The service conditions for BamCore Prime Walls are dry conditions of use, for which the equilibrium moisture content must be less than 16%. Uses in applications exceeding 16% moisture content are outside the scope of this TER.

9.4.5. The service conditions for BamCore Prime Walls with fire-retardant treatments are outside the scope of this TER.

9.4.6. Cutting and notching of BamCore Prime Walls is prohibited, except where specifically permitted by the manufacturer's recommendations or where the effects of such alterations are specifically considered in the design of the member by a registered design professional.

9.4.7. No Increases for duration of load are permitted.

9.4.8. BamCore Prime Walls shall be fabricated at BamCore LLC facilities located in Windsor, CA, with quality control inspections by an approved third-party quality control inspection agency.

9.5. Design

9.5.1. Building Designer Responsibility

9.5.1.1. Unless the AHJ allows otherwise, the construction documents shall be prepared by a Building Designer for the Building and shall be in accordance with *IRC* Section R106 and *IBC* Section 107.

9.5.1.2. The construction documents shall be accurate and reliable and shall provide the location, direction and magnitude of all applied loads and shall be in accordance with *IRC* Section R301 and *IBC* Section 1603.

9.5.2. Construction Documents

9.5.2.1. Construction documents shall be submitted to the Building Official for approval and shall contain the plans, specifications and details needed for the Building Official to approve such documents.

9.6. Responsibilities

9.6.1. The information contained herein is a product, material, detail, design and/or application TER evaluated in accordance with the referenced building codes, testing and/or analysis through the use of accepted engineering practice, experience and technical judgment.

9.6.2. DrJ TERs provide an assessment of only those attributes specifically addressed in the Products Evaluated or Code Compliance Process Evaluated sections.

9.6.3. The engineering evaluation was performed on the dates provided in this TER, within DrJ's professional scope of work.

9.6.4. This product is manufactured under a third-party quality control program in accordance with *IRC* Section R104.4 and R109.2 and *IBC* Section 104.4 and 110.4.

9.6.5. The actual design, suitability and use of this TER, for any particular building, is the responsibility of the Owner or the Owner's authorized agent, and the TER shall be reviewed for code compliance by the Building Official.

9.6.6. The use of this TER is dependent on the manufacturer's in-plant QC, the ISO/IEC 17020 third-party quality assurance program and procedures, proper installation per the manufacturer's instructions, the Building Official's inspection and any other code requirements that may apply to demonstrate and verify compliance with the applicable building code.

10. Identification:

10.1. BamCore Prime Wall System described in this TER are identified by labels that show the, product name, manufacturing location, TER number, and the name of the quality control inspection agency.

10.2. Additional technical information can be found at www.bamcore.com.

11. Review Schedule:

11.1. This TER is subject to periodic review and revision. For the most recent version of this TER, visit drjengineering.org/.

11.2. For information on the current status of this TER, contact DrJ Engineering.

- Mission and Professional Responsibilities
- Product Evaluation Policies
- Product Approval – Building Code, Administrative Law and P.E. Law

CHARACTERIZATION OF FRAMING FACTORS FOR LOW-RISE RESIDENTIAL BUILDING ENVELOPES IN CALIFORNIA

Characterization of Framing Factors for Low-Rise Residential Building Envelopes in California

CALIFORNIA ENERGY COMMISSION

CONSULTANT REPORT

DECEMBER 2001
P500-02-002

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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Legal Notice

Acknowledgements

This document, "Characterization of Framing Factors for Low-Rise Residential Building Envelopes in California" was prepared by Enermodal Engineering, Inc. under contract #400-00-002, for the California Energy Commission. Data was gathered primarily for use by the California Energy Commission in the development and implementation of building efficiency standards. The principal author of the report was Enermodal Engineering, Inc., 1554 Emerson Street, Denver, Colorado, 80218. Staff from the Energy Commission's Nonresidential Buildings Office who provided administrative and technical support included Jon Leber, Project Manager.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace. The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the "Characterization of Framing Factors for Low-Rise Residential Building Envelopes in California" project, Contract Number: #400-00-02, conducted by Enermodal Engineering, Inc., 1554 Emerson Street, Denver, Colorado, 80218. This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/pier/reports.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

The State of California has an energy code (Title 24) that requires building envelope assemblies to meet or exceed a specific R-value. Designers typically show compliance by adding up the thermal resistances of each layer in the assembly (i.e. parallel-path method). When there is more than one path through the assembly, for example through the insulation and through the wood framing in the case of a wood-framed wall, the thermal resistance through each path is calculated and area weighted.

Title 24 provides recommended values for the amount of area represented by framing. Unfortunately the source of this data is not well substantiated. The accuracy and suitability of framing data from other sources, such as the ASHRAE Handbook of Fundamentals is equally unsubstantiated. To address this problem, ASHRAE recently contracted Enermodal Engineering Ltd. (EEL) to conduct a survey of current framing practices in the four major census regions: North East, Mid-West, West and South [Enermodal, 2001]. The survey included detached, attached and multi-unit dwellings from each census region, for a total of 120 dwellings. Dwellings in high seismic or high wind regions were excluded from the survey. As a result, the State of California was not included in the ASHRAE survey. This study extends the methodology used in the ASHRAE project to the State of California.

Objectives

The overall goal of the project is to improve the accuracy of calculating overall envelope heat loss/gain. The objectives of this work are to:

- Develop a statistically representative set of framing factors (table next page) for low-rise dwellings in the State of California
- Identify differences in framing factors according to seismic region
- Quantify the distribution of framing within dwellings (e.g., walls, windows, ceilings)
- Present the information in a form that can be used by the California Energy Commission in its energy code

Sixty dwellings were audited during construction to assess the amount of framing. The dwellings were distributed in two seismic zones of California and three dwelling types (single detached, attached and multi-family) so as to obtain statistically significant samples for each dwelling type and zone. The size and style of dwelling within each group were selected to represent the range in that region. The study was restricted to wood-framed dwellings.

The amount of framing is expressed in two ways: gross and net. The gross values are the amount of framing in an envelope component (wall, floor, or ceiling) divided by the gross component area (including the area of any openings). The net values are the amount of framing in the component divided by the framed area (excluding the area of any openings). The framing factors based on the net area should be used whenever the net area is known.

Outcomes

A statistically representative set of framing factors was developed for low-rise dwellings in the State of California

Differences between the framing factors for seismic regions three and four were examined and found to be insignificant

The distribution of the framing has been quantified and relationships between framing factors and various dwelling characteristics are discussed

The framing factors were presented in tabular format that can be used by the California Energy Commission in its energy code

Conclusions

The following conclusions can be drawn about framing in dwellings.

- Approximately 18 percent of the gross wall area is taken up by openings for windows and doors. The amount of openings in floors and ceilings is negligible (less than one percent of the gross area)
- The framing factors for attached, detached and multi-family dwellings are very similar and can be represented by a single set of values
- There is very little difference in the framing factors for seismic zones three and four. A single set of values can represent both regions

The framing factors found in the California and the ASHRAE (national) study are summarized below. The results are very similar and as such, it appears that little additional framing is used in California to meet the seismic requirements.

Recommended Table of Framing Factors (all values in %)

Component	ASHRAE (National) Results	California Results
Window Area to Gross Wall Area	**12**	**12**
Door Area to Gross Wall Area	**5**	**7**
Rim Joist Area to Gross Wall Area	**4**	**Not Available – See Note**
Framing Factors	Net	Net
Ceiling	**7**	**7**
Wall	**25**	**27**
Floor	**12**	**Not Available – See Note**
Overall	**16**	**15**

Note: Since the vast majority of dwellings in the State of California are constructed on slab-on-grade foundations, there is not sufficient framed floor data to calculate framing factors related to the floor. Rim Joist Area is included in the Gross and Net Wall Areas. See also Framing Factor Definitions in Section 3.6 of this report.

Benefits to the State of California

This study has examined the amount of framing in residential building envelopes. This information improves the ability of engineering and design professionals to determine the effects of insulation strategies on building energy use.

By properly assessing the energy performance of building envelopes, the market will be encouraged to use the insulation strategies that provide optimal benefits. The net effect will be to reduce energy use in new California homes

Recommendations

Observations made during the site surveys suggest that architectural complexity and builder practices have an impact on the amount of framing used in the construction of low-rise dwellings. As these were not the focus areas in this study, the following are recommended:

Further research to identify those architectural features that require the most framing and create the largest thermal bridges.

Efficient framing methods (e.g. stack framing) should be further developed and a formal training program should be established to encourage builders to implement these practices.

Abstract

This study develops the understanding of the interaction of heat flow through the building envelope with differing framing practices. A field survey of 60 low-rise dwellings was conducted to develop a statistically representative set of framing factors for the State of California. The survey employed the methodology used in a similar ASHRAE sponsored survey of current framing practices in the four major census regions: North East, Mid-West, West and South. Detached, attached and multi-unit dwelling types were considered in both surveys.
Some of the key topics discussed in this study are:

- Framing factors for dwellings in non-seismic areas (i.e. from the ASHRAE study) are compared to those of seismic zones three and four in the State of California.
- The distribution of the framing is quantified and relationships between framing factors and various dwelling characteristics are discussed, and
- The framing factors are presented in a tabular format that can be easily adopted by practicing engineering and design professionals.

1.0 Introduction

Residential building energy codes (such as Title 24, ASHRAE 90.2, and the Model Energy Code) require building assemblies to meet or exceed a specific R-value. The requirements are usually a function of assembly type (e.g., wall, ceiling), climatic zone and in some cases fuel type. Designers typically show compliance with these requirements by performing a set of calculations that add up the thermal resistances of each layer in the assembly (i.e. parallel-path method). When there is more than one path through the assembly, for example through the insulation and through the wood framing in the case of a wood-framed wall, the thermal resistance through each path is calculated and area weighted.

Performing the area weighting requires knowledge of the relative amounts of each path in the assembly. For wood-frame buildings, this would seem to be a simple task since the studs are installed at equal spacings (e.g., 16 or 24" on center). The reality is that architectural features complicate residential construction and additional framing must be added in corners, around windows and doors, between floors and for blocking and bracing.

Having more accurate and representative framing percentages offers four benefits. First, more accurate data can have a significant effect on total-assembly R-value because heat transfer is much higher through the studs than through the insulation. For example, an eight-point increase in percentage framing (from 11 to 19 percent) reduces total-wall R-value by 12 percent. Second, using a more representative framing percentage may alter the relative cost-effectiveness between building assemblies (e.g., 2X6 vs. 2X4 with insulated sheathing vs. concrete block). Third, building assemblies that currently qualify in energy codes may no longer qualify if more representative framing factors are used (and vice versa). Fourth, the energy benefit of more efficient wood framing techniques (e.g., 2-stud corners) could be calculated (and accounted for in codes).

In September 1999, the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) contracted Enermodal Engineering Ltd. (EEL) to conduct a survey of current framing practices in the four major census regions: North East, Mid-West, West and South [Enermodal, 2001]. The survey included detached, attached and multi-unit dwellings from each census region, for a total of 120 dwellings. Dwellings in high seismic or high wind regions were excluded from the survey. As a result, the State of California was not included in the ASHRAE survey.

The California Energy Commission contracted Enermodal to extend the ASHRAE survey program to California. The overall goal of the project is to improve the accuracy of calculating overall envelope heat loss/gain.

1.1. Objectives

The objectives of this work are to:

- Develop a statistically representative set of framing factors for low-rise dwellings in the State of California,
- Identify differences in framing factors according to seismic region,
- Quantify the distribution of framing within dwellings (e.g., walls, windows, ceilings), and
- Present the information in a form that can be used by the California Energy Commission in its energy code.

1.2. Approach

Sixty dwellings were audited during construction to assess the amount of framing. The dwellings were distributed in two seismic zones (Zone Three and Zone Four) for three dwelling types (single detached, attached and multi-family) so as to obtain a statistically significant sample for each dwelling type and zone. The size and style of dwelling within each group were selected to represent the range in that zone. The data was analyzed in a database program to determine the amount and type of framing in the same manner as that used in the ASHRAE research project.
For the purpose of this research report, the following terms shall have the meanings indicated:
Attached Single-Family Dwelling: A single-family dwelling unit constructed in a row of attached units separated by property lines and with open space on at least two sides.
Detached Single-Family Dwelling: Any building which contains one dwelling, used, intended or designed to be built, and is occupied for living purposes.
Dwelling: A single unit providing complete independent living facilities for one or more persons, which includes permanent provisions for living, sleeping, eating, cooking, and sanitation [International Code Council-2000].
Multi-family Low-Rise Dwellings: A group of single-family units contained in a two- or three-story building where the occupants are non-transient in nature (e.g. apartment dwelling).
Steel-framed dwellings were not included so as to minimize the number of variables and to focus resources on the major framing type used in California.

2.0 Background Information

2.1. Published Values of Framing Factors

Several sources have published data on the percentage framing in wood frame dwellings. Table 1 lists the framing values which are used in the State of California Title 24 Energy Code calculation methods (adopted in 1998 and unchanged in 2001). Table 2 lists "typical" values of percent framing from previous versions of the ASHRAE Handbook of Fundamentals. Table 3 lists the values given in the Canadian Model National Energy Code for Houses. These sources represent a large variation in the amount of framing: from 15 percent to 25 percent for 16" stud spacing and from 9 percent to 22 percent for 24" stud spacing.

Table 1: Framing Factors from California Title 24

Component	16″ Stud Spacing	24″ Stud Spacing
Walls	**15%**	**12%**
Floors and Ceilings	**10%**	**7%**
***Overall*[1]**	***12.5%***	***9.5%***

[1] **– Overall values are estimated assuming equal area of floor/ceiling and above-grade walls**

Table 2: Framing Factors from the ASHRAE Handbook of Fundamentals

Component	1985 & 89 ASHRAE Handbook		1993 & 97 ASHRAE Handbook	
	16″ Studs	24″ Studs	16″ Studs	24″ Studs
Studs & Sills	**N/A**	**N/A**	**21%**	**18%**
Headers	**N/A**	**N/A**	**4%**	**4%**
Total	**15%**	**12%**	**25%**	**22%**

Table 3: Framing Factors from the Canadian Model National Energy Code for Dwellings

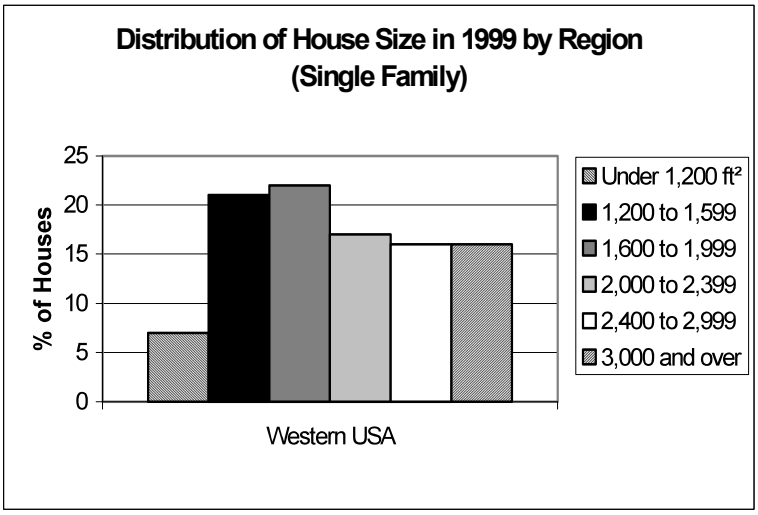
Component	16″ Stud Spacing	24″ Stud Spacing
Roofs, Ceilings, Floors	**10%**	**7%**
Above-Grade Walls	**19%**	**11%**
Below-Grade Walls	**17%**	**10%**
Overall[1]	**15%**	**9%**

[1] – Overall values are estimated assuming equal area of floor/ceiling and above-grade walls

The value of this data is limited in three ways. First, the source and representativeness of this data is not known. It does not appear to be based on a statistically valid sampling procedure. Second, given the wide range in dwelling types (e.g., detached, attached, multi-unit), regional construction practices and dwelling designs, it is likely that a single value is not representative of all cases. Third, the ASHRAE data does not provide values for ceilings and floors. It is important to know where the framing is to evaluate its impact on the assembly R-value. Framing in attics may have a lower effect on assembly R-value than for walls because ceiling joists are often covered by blown-in insulation.

2.2. Characteristics of Single-family Survey Sites

Single-family survey sites include both detached and attached dwellings (e.g. town houses, link homes (connected by party wall on one side and garage on other side) and semis (connected by party wall on one side only)). The majority of the single-family dwellings are stick-built (i.e. dwellings built on site using small structural members). Dwellings built using modular framing systems (i.e. factory-built) and other methods only account for two percent of the single-family dwellings constructed in Western USA in 1999 (US Census Bureau). The single-family dwellings constructed in 1999 are evenly divided between one story and two or more stories in height. Split-level homes represent only one percent of construction in Western USA. The majority are constructed on slab-on-grade floors. This study only includes stick-built dwellings. Figure 1 illustrates the distribution of single-family dwellings by dwelling size and geographic region. The ASHRAE framing survey used <2500 ft² (gross floor area) and >2500 ft² as the two categories to classify smaller and large dwellings. These categories are also used in this survey.



Adapted form US Census Bureau data

Figure 1: Distribution of Single-family Dwelling Sizes in 1999

The single-family survey sites in each zone were selected to achieve as close as possible the following criteria:

Framing Method: 100 percent stick built

Number of Stories: 50 percent one story, 50 percent two stories

Foundation Type: 90 percent slab on grade, 10 percent basement or crawlspace

Floor Area: 60 percent under 2500 ft², 40 percent over 2500 ft²

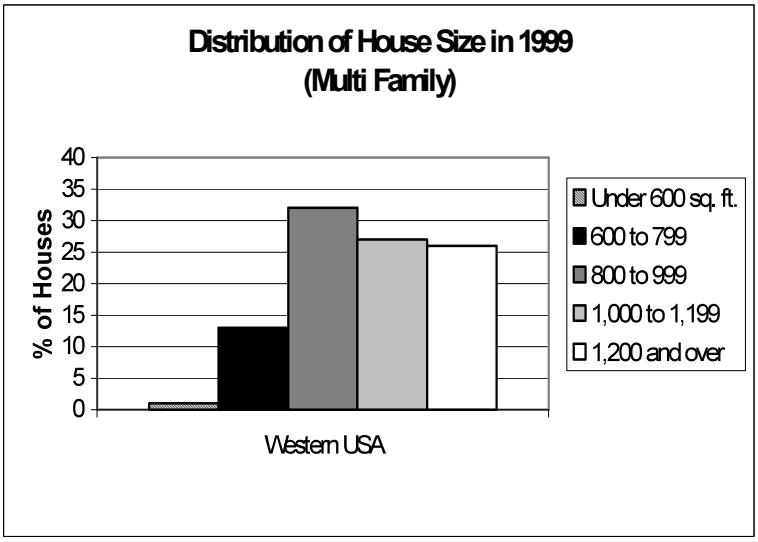
No more than three dwellings can be used from any single contractor

No dwelling plan can be used more than once

2.3. Characteristics of Multi-family Survey Sites

Multi-family buildings are made up of units that only have access from one side. They can contain multi-story units, one-story units, split-level units or a combination thereof. For the ASHRAE framing survey, Multi-unit buildings must contain a minimum of 8 units and must not be more than 3 stories in height. These rules were also applied to this survey.

Figure 2 illustrates the distribution of size of units in multi-family dwellings. The ASHRAE framing survey used <1000 ft² (gross floor area) and >1000 ft² as the two categories to classify smaller and large units. These categories are also used for this survey.



Adapted form US Census Bureau data

Figure 2: Distribution of Multi-Family Dwelling Sizes in 1999

The multi-family survey sites in each zone will be selected to achieve as close as possible the following criteria:

Framing Method: 100 percent stick built

Minimum Number of Units: 8

Maximum Number of Stories: 3

Foundation Type: 90 percent slab on grade, 10 percent basement or crawlspace

Floor Area: 40 percent under 1000 ft², 60 percent over 1000 ft²

No more than three buildings can be used from any single contractor

No building plan can be used more than once

3.0 Methodology for Determining Framing Factors

3.1. Overview

The method for determining framing factors consists of five steps as follows.

Step 1 - Locate Suitable Dwellings: The dwelling data must cover all regions of California and be representative of the type of dwelling built.

Step 2 – Audit Dwellings: For each selected dwelling, the auditors collected information on the amount of framing used in the ceiling, walls and floor. The audits were performed when the dwellings were framed but before insulation or drywall was added.

Step 3 – Enter Data into Database: An ACCESS database program was developed to assist the auditors in the collection and storage of the dwelling data

Step 4 – Analyze Dwelling Data: The project manager reviewed all dwelling data for consistency and suitability. The data was analyzed using the database program and conclusions drawn about the amount and type of framing.
Step 5 – Compare to ASHRAE Data: The final step was to determine how the California data compares to recently collected data in the ASHRAE project and account for any differences.

3.2. Geographic Distribution of Data

Two approaches were considered for determining the appropriate geographical distribution of the survey sites. In the first approach, the survey sites would be evenly distributed throughout the different regions that make up the study area. For example, the survey would include ten detached, ten attached and ten multi-family dwellings in each of the two seismic zones that cover California (30 dwellings in Zone 3 and 30 dwellings in Zone 4 = 60 dwellings). A similar approach was used in the ASHRAE framing survey (40 dwellings in each of Northeast, Mid West, West and South census regions). However, our experience from that project suggests that this may not be the best way to distribute the survey sites since it ignores the regional distribution of new construction. As an alternate approach, the geographic distribution of the survey sites would be set up to reflect the amount and type of construction occurring in different regions. If there are more detached dwellings constructed in one region than another, then more detached dwellings would be surveyed in that region. This was the approach taken to determining the geographic distribution of the survey sites in the State of California. Two parameters were considered: definition of seismic zones and census statistics of house starts.

The ICBO - Uniform Building Code (adopted in 1997) (UBC) is used as the basis for all residential construction in the State of California. The UBC defines certain seismic zones for the design of residential buildings to resist earthquake loads. The map in Figure 3 indicates the UBC seismic zones in the State of California. This map also shows the location of the cities included in the California new construction statistics. The size of the city marker suggests the relative amount of new construction taking place in that city.

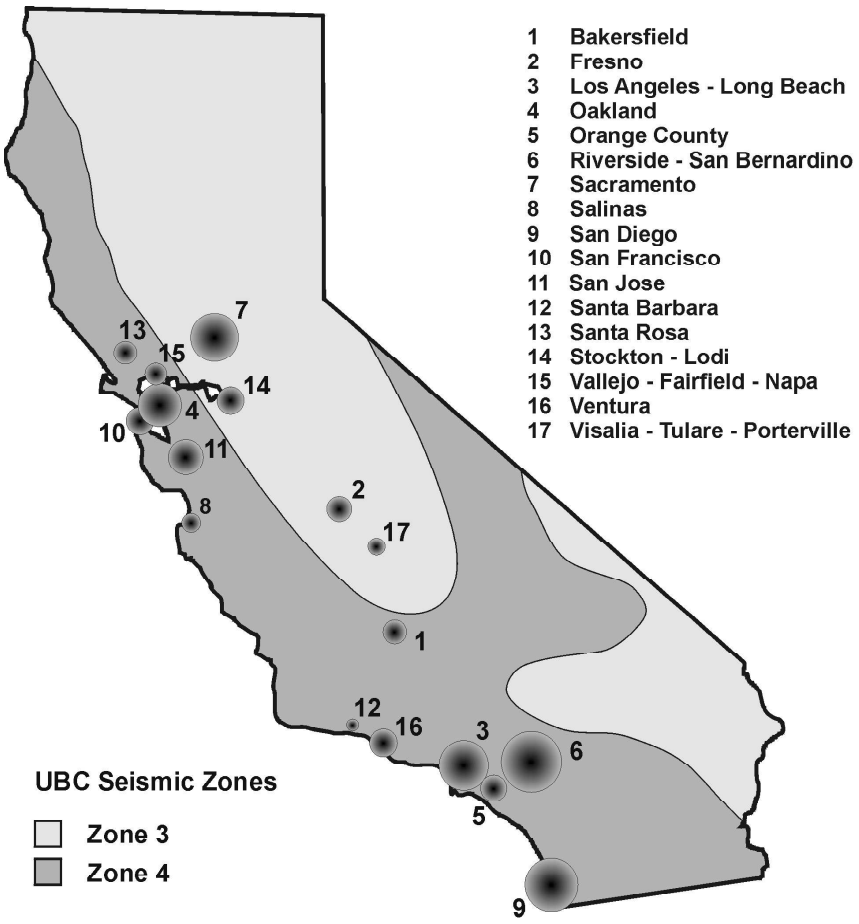


Figure 3: Map of UBC seismic zones and new construction in California

In California, the majority of the cities and over 80 percent of the 1999 new dwelling starts fall into UBC seismic Zone 4 (US Census Bureau data). Using an even distribution of survey sites, only 50 percent of the sites would be in Zone 4. Furthermore, the even distribution places too much emphasis on very small segments of the market. Multi-family dwelling construction in seismic Zone 3 accounts for only three percent of the new Dwelling starts in the State of California today (US Census Bureau data). Using an even distribution, almost 17 percent of the sites would be multi-family buildings from Zone 3.
Table 4 lists the distribution of survey sites used for this study:

Table 4: Distribution of Survey Sites

Dwelling Type	Seismic Zone 3	Seismic Zone 4	*Total*
Detached	11	19	***30***
Attached	2	16	***18***
Multi-unit	4	8	***12***
Total	***17***	***43***	***60***

This distribution of the survey sites reflects the distribution of 1999 new Dwelling starts (US Census Bureau data) with respect to seismic zone and dwelling type while ensuring that sample sizes are not too small to identify trends. This data provides reasonably accurate framing percentages for each dwelling type in California and identifies trends related to construction practices in the two seismic zones.

3.3. Representative Data

To ensure framing factors are meaningful, the dwellings surveyed are representative of new dwellings constructed in the State of California. Sixty sites are included in this study. These are distributed to reflect U. S. Census Bureau statistics, the seismic design requirements of the Uniform Building Code and conversations with housing experts from the State of California. The U. S. Census Bureau reported approximately 138,000 new dwelling starts (single and multi-family) in California in 1999. This represents an 11 percent increase over 1998 and a 26 percent increase over 1997. Figure 4 illustrates the distribution of single and multi-family dwellings constructed in 1999 by city.

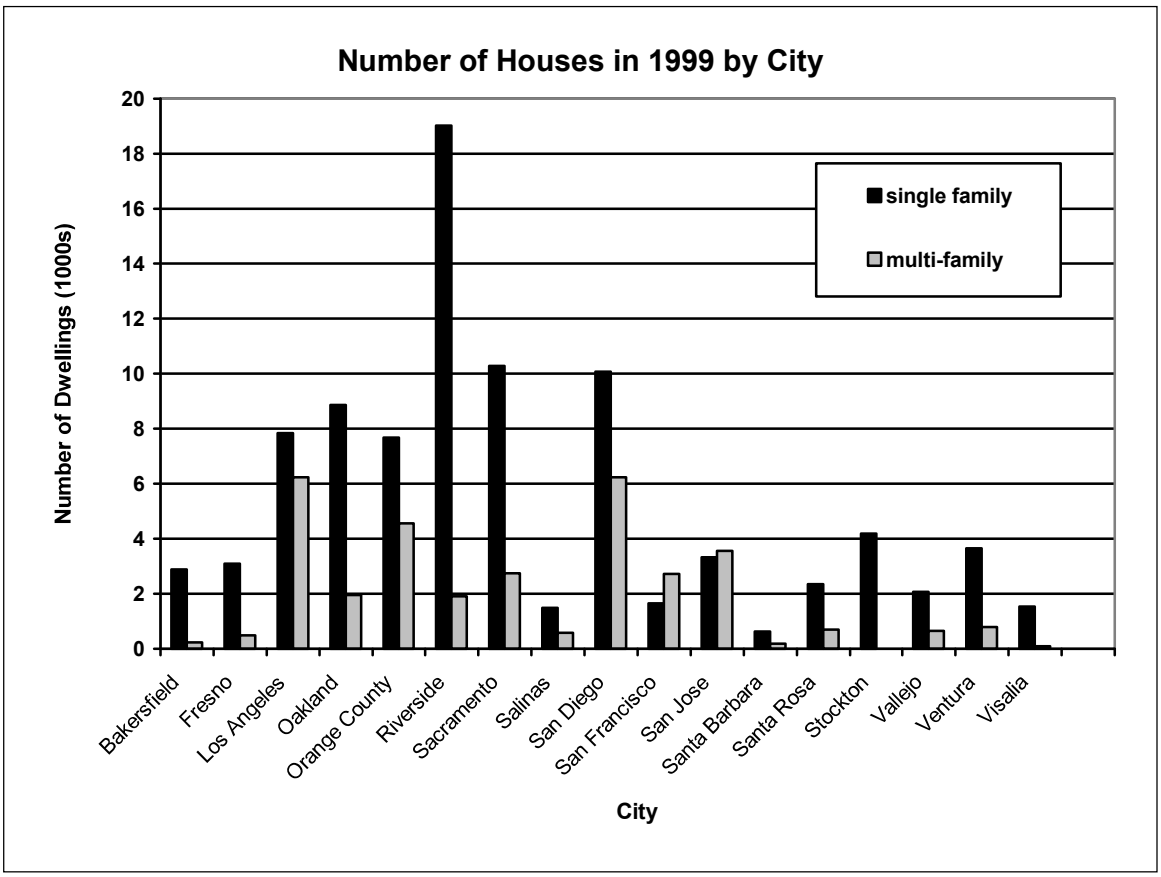


Figure 4: Number of Dwellings Constructed in California in 1999 by City

Over 73 percent of the dwellings constructed in 1999 are single-family dwellings. The majority of the multi-family dwellings are constructed in or near the major cities (i.e. Los Angeles, San Diego, San Jose and San Francisco). The ratio of single-family to multi-family dwellings surveyed in this study reflects the 1999 new dwelling statistics.

3.4. Data Collection Procedure

The audits were performed during construction after the framing was up but before it was enclosed with insulation and drywall. At this stage, the amount of framing can be visually verified, including additional framing not shown on the drawings. The data collection process was

Identify survey sites

Arrange access with the builder

Get dimensioned drawings (if available)

Visit the site at the appropriate construction phase

Photograph typical and unique construction details

Count/measure all framing members and record this information in the ACCESS-based computer program

Return the data tables to project manager for statistical analysis

3.5. Data Analysis Procedure

This project involves the collection and analysis of a large amount of data – a job well suited to a database program. An ACCESS-based computer program was developed to facilitate data collection and analysis. In essence, the ACCESS program serves as a series of electronic data collection forms and a standardized method for calculating framing factors. Appendix I shows the software screens and user manual. The auditor would take the program (on a laptop computer) to the site and collect and enter the data at one time.

The ACCESS computer program offered several advantages over manual data collection. First, the data collection and data entry was done on site, thereby reducing time and potential for errors in recording the data and transferring it from field notes. Second, some data analysis can be done on site for the dwelling being inspected. Thus, the auditor gets immediate feedback on the results for the dwelling. If one or more of the calculated quantities looks unreasonable, the auditor can re-check the data on site. Third, a set of standardized input forms helped to reduce differences in data collection procedures over the survey period.

The auditors entered data for individual dwellings. Their audit results were sent to the project manager for review, amalgamation and computation of the important framing characteristics. The program is able to aggregate and disaggregate the information as needed.

3.6. Framing Factor Definitions

The ACCESS computer program calculates a range of dwelling framing characteristics. The definitions of these framing factors are given below.

Ceiling Framing Factor: ratio of framing area in insulated ceilings to the ceiling area (either gross or net). Framing includes joists, trusses, blocking and framing around skylights and attic hatches that partially or fully penetrate the insulation. Rim joists are not included.

Ceiling Opening to Ceiling Area: ratio of the opening areas in the ceiling to the gross ceiling area (including skylights and access hatches).

Corner Height to Wall Area: ratio of the total height of all corners in insulated walls to the wall area in units of inches per square foot. This is used as a measure of the complexity of the floor plan.

Door Area to Wall Area: ratio of the rough door opening area to the gross wall area (including window and door areas). Swinging and sliding glass doors are considered doors. The reader should note that the door area may include transom or sidelight windows.

Floor Framing Factor: ratio of framing area in insulated floors to the floor area (either gross or net). Framing includes joists, blocking and framing around access hatches that penetrate the insulation. Rim joists are not included.

Floor Opening to Floor Area: ratio of the opening areas in the floor to the gross floor area (including access hatches).

Gross Insulated Ceiling Area: surface area (in the direction perpendicular to heat flow) of all insulated ceilings between heated areas and the outside or unheated areas (such as attics). The ceiling area is based on exterior or outside ceiling dimensions. The ceiling dimensions are to the outside of the framing and include the area of any skylights or attic hatches.

Gross Insulated Floor Area: surface area (in the direction perpendicular to heat flow) of all insulated floors between conditioned spaces and the outside or unconditioned spaces (such as crawlspaces and unheated basements). Non-framed floors such as concrete (e.g. slab on grade) floors are excluded. The floor area is based on exterior or outside floor dimensions. The floor dimensions are to the outside of the framing.

Gross Insulated Wall Area: surface area (in the direction perpendicular to heat flow) of all insulated walls between conditioned spaces and the outside or unconditioned spaces (such as garages and porches). The wall area is based on exterior or outside wall dimensions. The wall width is to the outside of the framing. The wall height is from the bottom of the main floor to the inside of the ceiling framing, including the height of any wall/interior floors junctions (i.e. including rim joists). The area of any windows or doors is included.
Net Insulated Ceiling Area: is the gross ceiling area less the area of any skylights or attic hatches.
Net Insulated Floor Area: is the gross floor area less the area of any floor hatches.
Net Insulated Wall Area: is the gross wall area less the area of windows, doors. The net insulated wall area includes the area of rim joists.
Overall Framing Factor: ratio of all framing areas in the insulated floors, ceilings and walls to the total area of insulated floors, ceilings and walls (either gross or net). Non-framed floors, ceilings and walls (e.g. concrete or solid masonry) are not included in the calculation.
Rim Joist Area to Wall Area: ratio of the rim joist area to the gross wall area
Total Floor Area: total area of all floors (above conditioned & unconditioned spaces). This area is used by builders, realtors and homeowners to describe the size of the dwelling.
Window Area to Wall Area: ratio of the rough window opening area to the gross wall area (including window and door areas). Swinging and sliding glass doors are considered doors.
Wall Framing Factor: ratio of the framing area in the insulated walls to the wall area (either gross or net). Framing includes headers, sill plates, studs, framing around doors and windows, corners, blocking and where floor joists penetrate the wall insulation layer. Framing that does not bridge the insulation (e.g., exterior or interior strapping, let-in bracing, rim joist) is excluded.

4.0 Results of Dwelling Audits

4.1. Distribution of Dwelling Audits

The audits were performed over the period from Fall 2000 to Spring 2001. The results are summarized by seismic zone and dwelling type in Table 5, Table 6, and Table 7 show the distribution of the dwellings characteristics. The data from these dwellings has been analyzed and is presented in the remainder of this section.

Table 5: Number of Dwelling Type by Zone

Dwelling Type	Seismic Zone 3	Seismic Zone 4	Total
Detached	11	19	30
Attached	2	16	18
Multi-unit	4	8	12
Total	17	43	60

Table 6: Single Detached and Attached Dwelling Characteristics

Number of Buildings in Each Zone			
		Seismic Zone 3	**Seismic Zone 4**
Area	**Under 2400 sq. ft.**	8	30
	Over 2400 sq. ft.	5	5
Stories	**1 Story**	11	9
	2 or more	2	26
	Split	0	0
Basement	**Full**	0	0
	Slab-on-grade	13	35
	Crawlspace	0	0

Table 7 sets out criteria for selecting the 12 multi-family buildings. Since there is less variety in multi-family dwellings than there is in detached and attached dwellings, the only selection criterion for multi-family buildings is area/unit.

Table 7: Multi-Family Dwelling Characteristics

Number of Buildings by Zone			
		Seismic Zone 3	**Seismic Zone 4**
Area	< 1000 sq. ft./unit	2	5
	> 1000 sq. ft./unit	2	3

4.2. Framing Factors for Detached Dwelling

Table 8 summarizes the framing factors for the 30 detached dwellings. The individual dwelling values are contained in Appendix II. The floor framing factor is labeled as "not available" because none of the surveyed dwellings contained a framed floor. Windows and doors account for 17 percent of the gross wall area. As discussed in Section 3.6, the door area includes swinging and sliding glass doors and door area includes glazed areas around doors (e.g., transoms and sidelites). The net ceiling and wall framing factors are 7 and 26 percent respectively.

Table 8: Framing Factors for Detached Dwellings (%, unless noted)[1]

Component	Zone 3	Zone 4	All
Area and Length Ratios			
Window Area to Wall Area	**12.8** ± 2.8	**11.2** ± 4.1	**11.8** ± 3.8
Door Area to Wall Area	**6.2** ± 3.0	**4.5** ± 1.4	**5.1** ± 2.2
Corner Height to Wall Area (inches/ft²)	**0.5** ± 0.2	**0.5** ± 0.1	**0.5** ± 0.1
Exposed Perimeter to Floor Area (inches/ft²)	**0.5** ± 0.2	**0.4** ± 0.2	**0.4** ± 0.2
Ceiling Opening to Wall Area	**0.3** ± 0.2	**0.4** ± 0.2	**0.4** ± 0.2
Floor Opening to Floor Area	**0.0** ± 0.0	**0.0** ± 0.0	**0.0** ± 0.0
Framing Factors Based on Gross Areas			
Ceiling	**7.2** ± 1.4	**6.7** ± 0.5	**6.9** ± 0.9
Wall	**22.3** ± 2.2	**21.1** ± 2.0	**21.6** ± 2.1
Floor	**Not Available**	**Not Available**	**Not Available**
Overall	**11.7** ± 1.6	**11.5** ± 2.0	**11.6** ± 1.8
Framing Factors Based on Net Areas			
Ceiling	**7.2** ± 1.4	**6.7** ± 0.5	**6.9** ± 0.9
Wall	**27.6** ± 2.9	**25.2** ± 3.3	**26.1** ± 3.3
Floor	**Not Available**	**Not Available**	**Not Available**
Overall	**13.3** ± 2.2	**12.9** ± 2.7	**13.0** ± 2.5

[1] + or - values indicate one standard deviation

4.3. Framing Factors for Attached Dwelling

Table 9 summarizes the framing factors for the 18 attached dwelling surveys. Appendix II contains the individual values. The results are similar to those for detached dwellings. The

percentage of windows and doors is slightly higher at 19 percent because the common wall reduces the exterior wall area. Nevertheless, the net ceiling and wall framing factors are almost identical at 7 and 27 percent.

Table 9: Framing Factors for Attached Dwellings (%, unless noted)[1]

Component	Zone 3	Zone 4	All
Area and Length Ratios			
Window Area to Wall Area	**12.1** ± 0.4	**12.0** ± 3.1	**12.0** ± 3.2
Door Area to Wall Area	**9.0** ± 4.2	**6.6** ± 2.6	**6.9** ± 2.7
Corner Height to Wall Area (inches/ft²)	**0.7** ± 0.1	**0.8** ± 0.3	**0.8** ± 0.3
Exposed Perimeter to Floor Area (inches/ft²)	**0.0** ± 0.0	**0.2** ± 0.1	**0.2** ± 0.1
Ceiling Opening to Wall Area	**0.4** ± 0.4	**0.6** ± 0.3	**0.6** ± 0.3
Floor Opening to Floor Area	**0.0** ± 0.0	**0.0** ± 0.0	**0.0** ± 0.0
Framing Factors Based on Gross Area			
Ceiling	**6.9** ± 0.7	**7.4** ± 1.2	**7.3** ± 1.1
Wall	**18.0** ± 0.2	**22.0** ± 1.2	**21.6** ± 1.3
Floor	**Not Available**	**Not Available**	**Not Available**
Overall	**9.4** ± 1.1	**12.6** ± 2.9	**12.2** ± 2.8
Framing Factors Based on Net Area			
Ceiling	**6.9** ± 0.7	**7.4** ± 1.2	**7.4** ± 1.1
Wall	**22.8** ± 1.3	**27.1** ± 2.1	**26.7** ± 1.3
Floor	**Not Available**	**Not Available**	**Not Available**
Overall	**10.5** ± 1.7	**14.4** ± 3.6	**14.0** ± 3.5

[1] = or ± values indicate one standard deviation

4.4. Framing Factors for Multi-Unit Dwelling

Table 10 summarizes the results for the 12 multi-family dwelling surveys. Appendix II contains the individual dwelling values. The ceiling and wall framing factors for the multi-family dwellings are almost identical to those for attached and detached dwellings.
Zone Four has higher seismic loading requirements, so it was expected that dwellings in Zone Four would have higher framing factors than dwellings in Zone Three. Surprisingly, the framing factors of these zones are very similar for all three housing types.

Table 10: Framing Factors for Multi-Family Dwellings (%, unless noted)[1]

Component	Zone 3	Zone 4	All
Area and Length Ratios			
Window Area to Wall Area	**10.0** ± 7.5	**11.1** ± 2.5	**10.8** ± 4.6
Door Area to Wall Area	**8.1** ± 1.4	**11.1** ± 3.0	**10.1** ± 2.9
Corner Height to Wall Area (inches/ft²)	**0.9** ± 0.2	**0.9** ± 0.1	**0.9** ± 0.2
Exposed Perimeter to Floor Area (inches/ft²)	**0.7** ± 0.3	**0.5** ± 0.1	**0.6** ± 0.2
Ceiling Opening to Wall Area	**0.3** ± 0.3	**0.5** ± 0.2	**0.4** ± 0.3
Floor Opening to Floor Area	**0.0** ± 0.0	**0.0** ± 0.0	**0.0** ± 0.0
Framing Factors Based on Gross Areas			
Ceiling	**6.7** ± 0.6	**7.0** ± 2.8	**6.9** ± 2.3
Wall	**20.7** ± 0.4	**21.7** ± 0.9	**21.4** ± 1.3
Floor	**Not Available**	**Not Available**	**Not Available**
Overall	**16.6** ± 0.5	**17.5** ± 1.6	**17.2** ± 2.1
Framing Factors Based on Net Areas			
Ceiling	**6.7** ± 0.9	**6.6** ± 3.0	**6.7** ± 2.5
Wall	**25.4** ± 2.3	**28.1** ± 2.2	**27.2** ± 2.5
Floor	**Not Available**	**Not Available**	**Not Available**
Overall	**19.8** ± 0.9	**21.9** ± 2.4	**21.2** ± 2.9

[1] + or - values indicate one standard deviation

4.5. Analysis of Framing Factors

Sections 4.2 to 4.4 presented the framing factors as a function of dwellings type and region. In this section, the effect of other dwelling characteristics on framing factors is studied, specifically floor area and number of stories.

Figure 5, Figure 6, and Figure 7 show the overall net framing factor as a function of total floor area. The overall framing percentage varies from 9 to 18 percent for detached dwellings, however, there appears to be no correlation between dwelling size and the amount of framing. The same result seems to apply for attached and multi-family dwellings. Overall framing factors range from 10 to 23 percent and 8 to 24 percent respectively. Neither shows a strong relationship between framing factor and dwelling size.

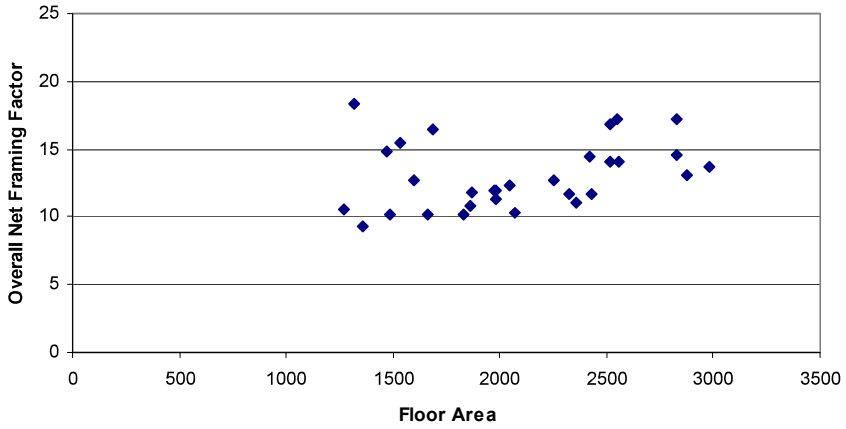


Figure 5: Overall Net Framing Factors vs. Floor Area for Detached Dwellings

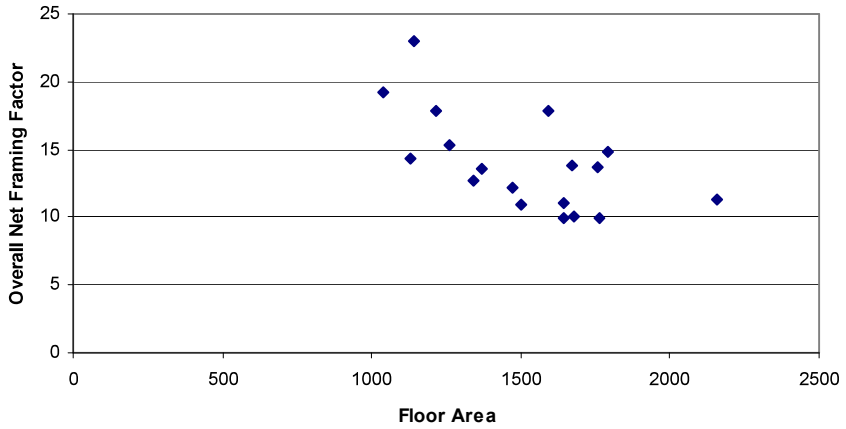


Figure 6: Overall Net Framing Factors vs. Floor Area for Attached Dwellings

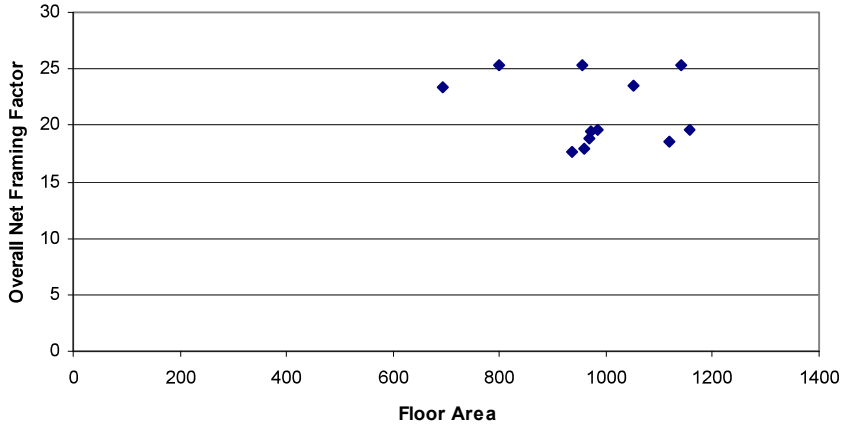


Figure 7: Overall Net Framing Factors vs. Floor Area for Multi-Family Dwellings

Ceilings and floors tend to have lower framing factors than walls. As a result, the area of ceilings and exposed floors (e.g. above garages) can dramatically affect overall framing factors. Therefore, the relationships between wall framing factors and various building characteristics may be evident. Figure 8, Figure 9, and Figure 10 illustrate the relationship between floor area and wall net framing factor. The wall net framing factors range from 19 to 33 percent, 22 to 32 percent and 24 to 34 percent for detached, attached and multi-family dwellings respectively. Correlation analysis indicates that there is a relationship between wall net framing factor and floor area for detached dwellings (correlation coefficient of 0.62), but not attached and multi-family dwellings.

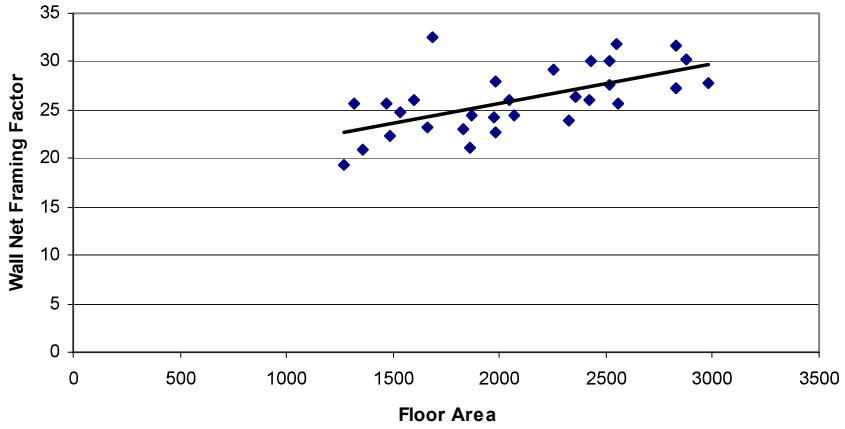


Figure 8: Wall Net Framing Factors vs. Floor Area for Detached Dwellings

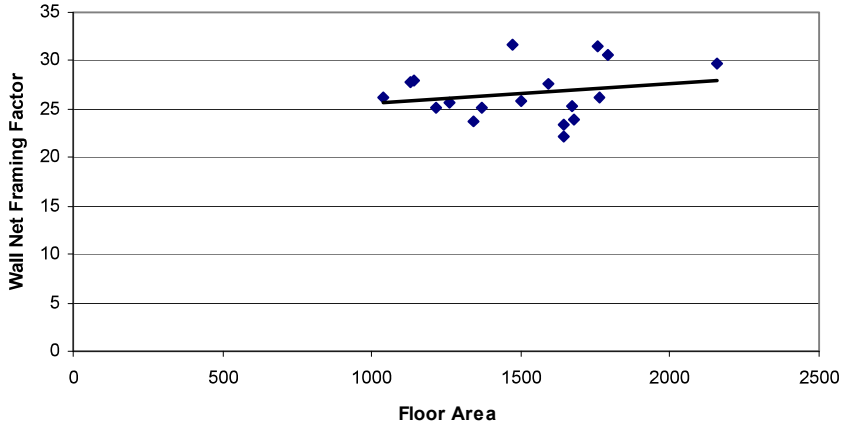


Figure 9: Wall Net Framing Factors vs. Floor Area for Attached Dwellings

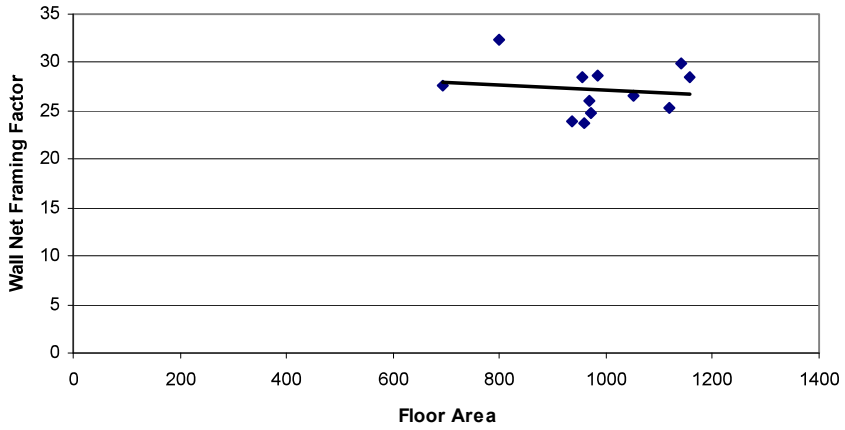


Figure 10: Wall Net Framing Factors vs. Floor Area for Multi-Family Dwellings

Figure 11 shows the effect of the number of stories on overall net framing factor. The framing factor increases with the number of stories with an average of 13, 16 and 23 percent for one, two, and three story dwellings. There are two reasons for this increase. First, single story dwellings have a larger ceiling area than multi-story buildings. Because ceilings have a low framing factor, increasing the ceiling area decreases the overall framing factor. Second, for multi-story dwellings, the amount of wall framing in lower floors is increased in order to carry the weight of the floors above. For example, some dwellings had studs spaced on 12-inch centers for the first floor and on 16-inch centers for the upper floors.

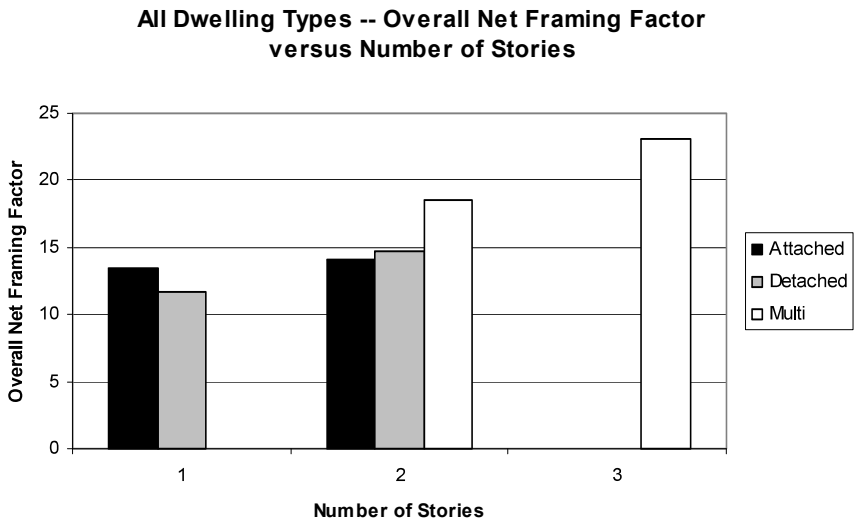


Figure 11: Effect of Number of Stories on Overall Framing Factors

A similar trend is evident in Figure 12, which compares number of stories and wall net framing factor. The increase in framing factor with number of stories is smaller because the effect of the ceiling has been removed.

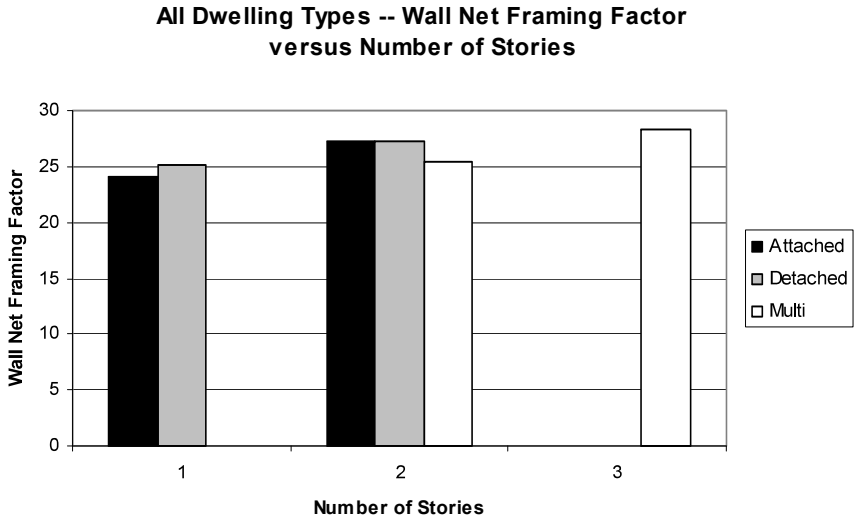


Figure 12: Effect of Number of Stories on Wall Framing Factor

The corner height to wall area ratio provides a measure of the complexity of the floor plan. A simple rectangular floor plan will only have four corners, while a more complicated, "H-shaped" plan would have 12 corners and a higher ratio. Because more framing is required at corners, it is reasonable that there may be a relationship between wall framing factor and corner height. However, Figure 13, Figure 14, and Figure 15 do not indicate any relationship.

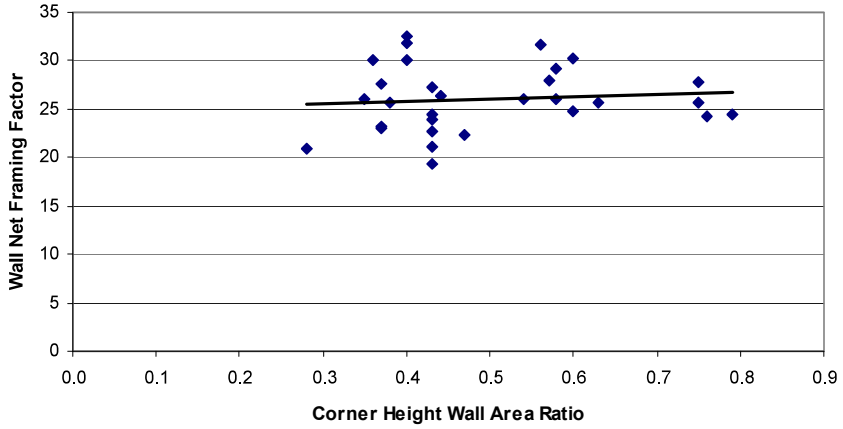


Figure 13: Wall Net Framing Factor vs. Corner Height to Wall Area Ratio for Detached Dwellings

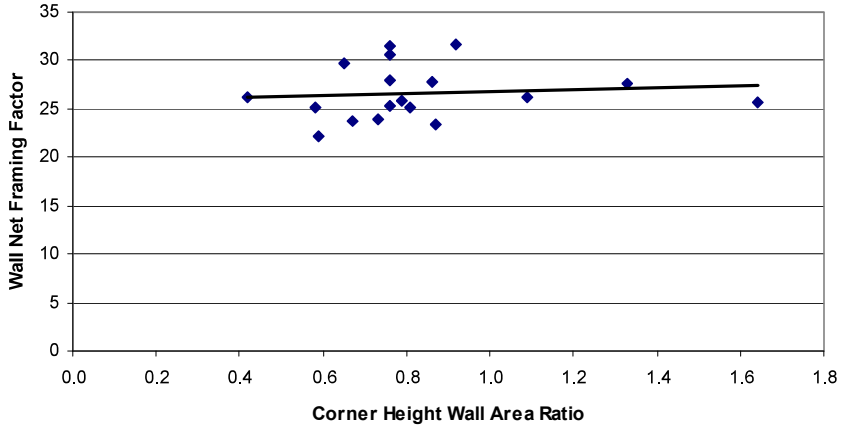


Figure 14: Wall Net Framing Factor vs. Corner Height to Wall Area Ratio for Attached Dwellings

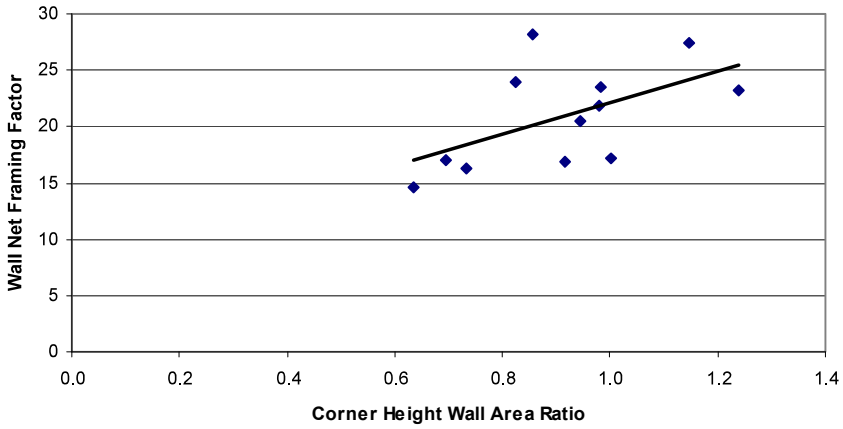


Figure 15: Wall Net Framing Factor vs. Corner Height to Wall Area Ratio for Multi-Family Dwellings

Window and door openings require that lintels (headers), king-studs, jack-studs and cripple studs be provided to distribute wind loads and gravity loads from above the openings. These pieces of lumber increase the amount of framing that goes into a wall, increasing the framing factor. Figure 16, Figure 17, and Figure 18 all show a relationship between wall net framing factor and the sum of the window to wall area and the door to wall area ratios. Correlation analysis indicates that this dwelling characteristic has the strongest relationship with wall net framing factor.

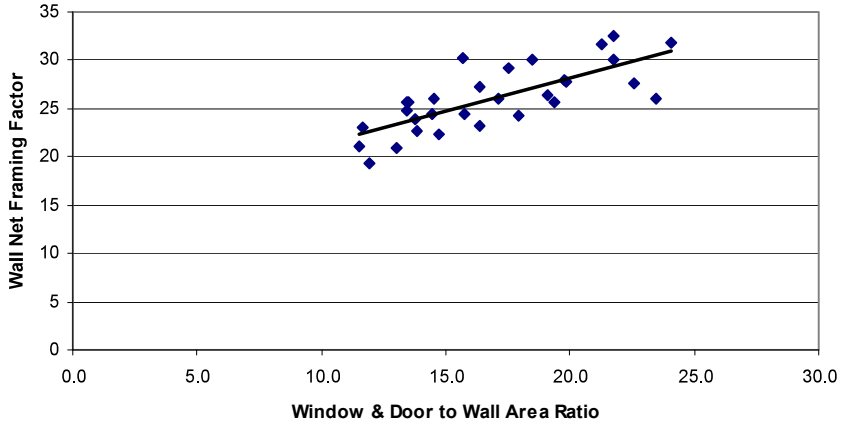


Figure 16: Wall Net Framing Factor vs. Window + Door to Wall Area Ratio for Detached Dwellings

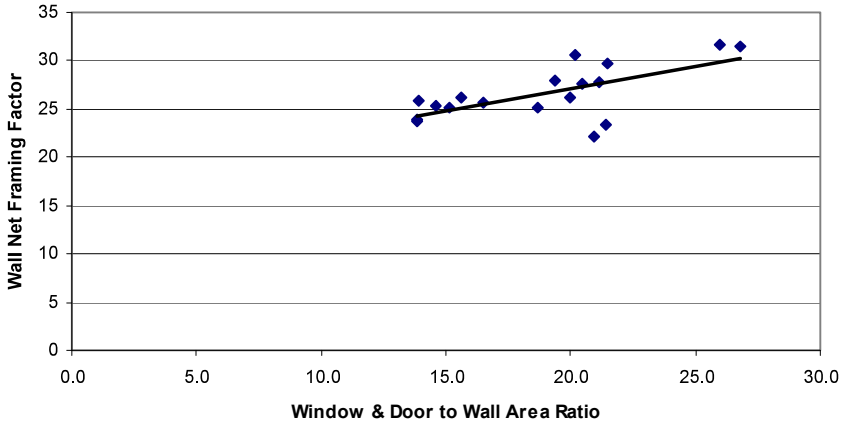


Figure 17: Wall Net Framing Factor vs. Window + Door to Wall Area Ratio for Attached Dwellings

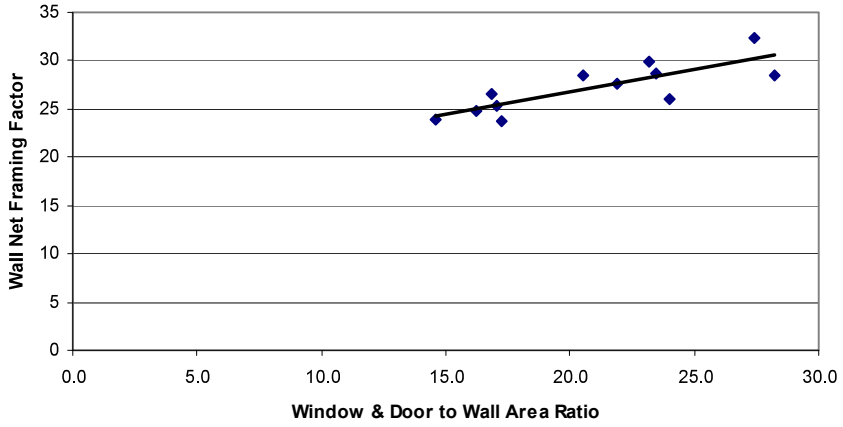


Figure 18: Wall Net Framing Factor vs. Window + Door to Wall Area Ratio for Multi-Family Dwellings

In the ASHRAE study, the effect of dwelling characteristics on framing factors was also studied. No correlation was found between dwelling size and the amount of framing. Furthermore, in the ASHRAE study there was less change in framing factor with number of stories. In addition to studying the effect of floor area and number of stories, the ASHRAE study looked at type of wall framing (2X4 or 2X6).

Some structural and economic arguments have been made to support the use of 2x6 framing on 24 inch spacing. However, most of the dwellings surveyed used 2X4 studs on 16 inch spacing for the wall framing, with the remainder using 2X6 studs on 16 inch spacing. In many cases, a combination of the two stud sizes is used to deal with unique or difficult framing details. The ASHRAE study showed that there is very little difference in wall framing factor between the two stud sizes. A review of the individual files showed that 2X6 studs were used more for structural reasons such as high ceilings than to take advantage of a wider stud spacing (e.g., 24 inch centers). The same result applies to the California study, since all of the dwellings were framed with studs on 16-inch centers. No comment can be made on framing factors for 24-inch stud spacing because of the lack of data for 24-inch spacing in both the ASHRAE and California studies.

Based on the analysis that accompanies Figures 5 to 18 and a review of the individual survey files, it would appear that window and door openings, floor area and number of stories all have an influence on the wall net framing factor. Relationships between these dwelling characteristics and the overall net framing factor are not always as obvious, and there is not a single dominant characteristic that defines either the wall or overall framing factor. Site observations indicate that there are many characteristics that affect the framing factors including:

building type (i.e. detached, attached, multi),

number and size of openings (e.g., windows and doors),

floor area,

number of stories,

type of wall framing (2X4 or 2X6),

architectural complexity,

builder practices (e.g., 2-stud vs. 3-stud corners)

It is the combination of all the characteristics listed above which results in the variation in framing factors. Although not discussed in this report, architectural complexity and builder practices may have the largest impact on framing factor. There is a wide range in framing factors for the different builders, however, the framing factors for two different, but architecturally similar, dwelling plans from the same builder showed little variation. In the ASHRAE study, five of the eight pairs of dwellings framed by the same builder have wall framing factors within one percent. Framers tend to learn on the job in small groups and there is no standardized method for framing. In addition, small architectural details (e.g., framing around a bay window) can greatly increase the amount of framing.

4.6. Statistical Confidence

Given the small sample size of this study, it is useful to estimate how well the data represents the greater population of dwellings in California. Table 11 summarizes the expected range for mean framing factors at 95 percent confidence. In other words, one can be 95 percent confident that another study of framing would produce mean framing factors within the ranges given in the table. For example, the mean of the detached wall net framing factors would fall somewhere between 24.9 percent and 27.3 percent. Since the ranges are relatively tight, the samples represent the greater population well.

Table 11: Range for Mean Net Framing Factors at 95% Confidence

Component	Detached	Attached	Multi-Family
Ceiling	6.6 to 7.2	6.9 to 7.9	5.3 to 8.1
Wall	24.9 to 27.3	25.6 to 27.8	25.8 to 28.6
Floor	Not Available	Not Available	Not Available
Overall	12.1 to 13.9	12.4 to 15.6	19.6 to 22.8

5.0 Comparison to ASHRAE Results

Table 12 compares the California results with the national results from the ASHRAE project [Enermodal, 2001]. Dwellings throughout North America are made stable by framing within the buildings. It was expected that dwellings in high seismic regions would have higher framing factors than other dwellings, yet Table 12: shows that the framing factors of buildings in high seismic regions -- zones three and four of California -- are almost identical to those of other buildings in the Northeast, Midwest, South, and West regions of the United States. Ceiling, wall, and overall framing factors are within one standard deviation of each other for both the California Energy Commission and the ASHRAE results.

The framing factor for floors in California is not available because the dwellings surveyed in that area have concrete slab-on-grade floors.

Table 12: California Results Compared to ASHRAE Results (all values in %)[1]

Component	ASHRAE (National) Results	California Results
Window Area to Gross Wall Area	**11.5** ± 4.7	**11.6** ± 3.8
Door Area to Gross Wall Area	**5.2** ± 3.7	**6.7** ± 3.3
Rim Joist Area to Gross Wall Area	**4.3** ± 3.3	**Not Available**
Framing Factors	Net	Net
Ceiling	**6.9** ± 2.1	**7.0** ± 1.5
Wall	**25.4** ± 4.5	**26.5** ± 3.0
Floor	**11.9** ± 5.1	**Not Available**
Overall	**15.5** ± 3.8	**14.9** ± 4.3

[1] + or -values indicate one standard deviation

6.0 Conclusions and Recommendations

6.1. Conclusions

Audits of 60 dwellings were conducted in two seismic regions for three dwelling types. The following conclusions can be drawn about framing in dwellings.
The following conclusions can be drawn about framing in dwellings.

- Approximately 18 percent of the gross wall area is taken up by openings for windows and doors. The amount of openings in floors and ceilings is negligible (less than one percent of the gross area)
- The framing factors for attached, detached and multi-family dwellings are very similar and can be represented by a single set of values
- There is very little difference in the framing factors for seismic zones three and four. A single set of values can represent both regions

Table 13 summarizes the framing factors found in the California and the ASHRAE (national) studies. The results are very similar and as such, it appears that little additional framing is used in California to meet the seismic requirements.

Table 13: Recommended Table of Framing Factors (all values in %)

Component	ASHRAE (National) Results	California Results
Window Area to Gross Wall Area	**12**	**12**
Door Area to Gross Wall Area	**5**	**7**
Rim Joist Area to Gross Wall Area	**4**	**Not Available – See Note**
Framing Factors	Net	Net
Ceiling	**7**	**7**
Wall	**25**	**27**
Floor	**12**	**Not Available – See Note**
Overall	**16**	**15**

Note: Since the vast majority of dwellings in the State of California are constructed on slab-on-grade foundations, there is not sufficient framed floor data to calculate framing factors related to the floor. Rim Joist Area is included in the Gross and Net Wall Areas.

6.2. Benefits to the State of California

This study has examined the amount of framing in residential building envelopes. This information improves the ability of engineering and design professionals to determine the effects of insulation strategies on building energy use.

By properly assessing the energy performance of building envelopes, the market will be encouraged to use the insulation strategies that provide optimal benefits. The net effect will be to reduce energy use in new California homes

6.3. Recommendations

Observations made during the site surveys suggest that architectural complexity and builder practices have an impact on the amount of framing used in the construction of low-rise dwellings. As these were not the focus areas in this study, the following are recommended:

- Further research to identify those architectural features that require the most framing and create the largest thermal bridges.
- Efficient framing methods (e.g. stack framing) should be further developed and a formal training program should be established to encourage builders to implement these practices.

7.0 References

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US Census Bureau, Washington, DC (USA)

Appendix I – Procedure for Dwelling Data Collection

A large amount of data must be collected to establish statistically valid framing factors for wood-framed dwellings. A database program was developed as the basis of the framing survey. Each Dwelling auditor used a copy of the program to enter, store and process survey data. This section explains the format of the data entry forms and outlines the type of data collected.
The flowchart in Figure I - 1 illustrates the relationship between the 11 entry forms that make up the database program. General information about the site is entered in the ***Site Survey*** form; the ***Ceilings***, ***Walls*** and ***Floors*** forms are used to describe the general framing elements that make up the dwelling; and framing details are entered in the ***Openings***, ***Intersections*** and ***Corners*** forms.

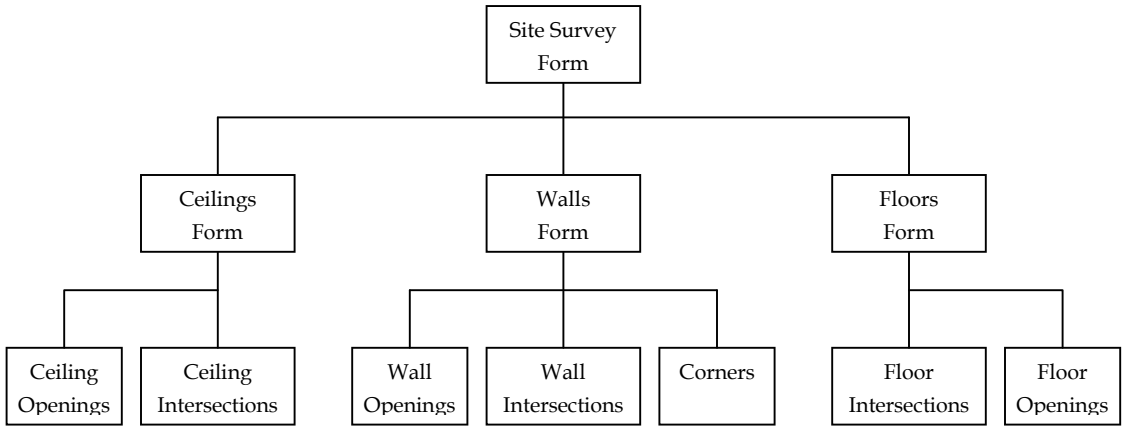


Figure I - 1: Database Structure

The forms that are lower in the database structure shown in Figure I - 1 contain more detail and are accessed from the less detailed forms higher up in the flowchart. Surveyors will work from general to specific (i.e., down the flowchart) when entering data. The program will work from specific to general (i.e., up the flowchart) when processing data. Sections 2.1 through 2.4 describe the type of data entered into the database. Section 3 describes how these data are processed to determine the framing factors.

Site Survey Form

The ***Site Survey*** (Figure I - 2) form has three functions: to navigate through the database of survey sites, to summarize general information about each site, and to access the site details in the ***Ceiling***, ***Wall*** and ***Floor*** forms.

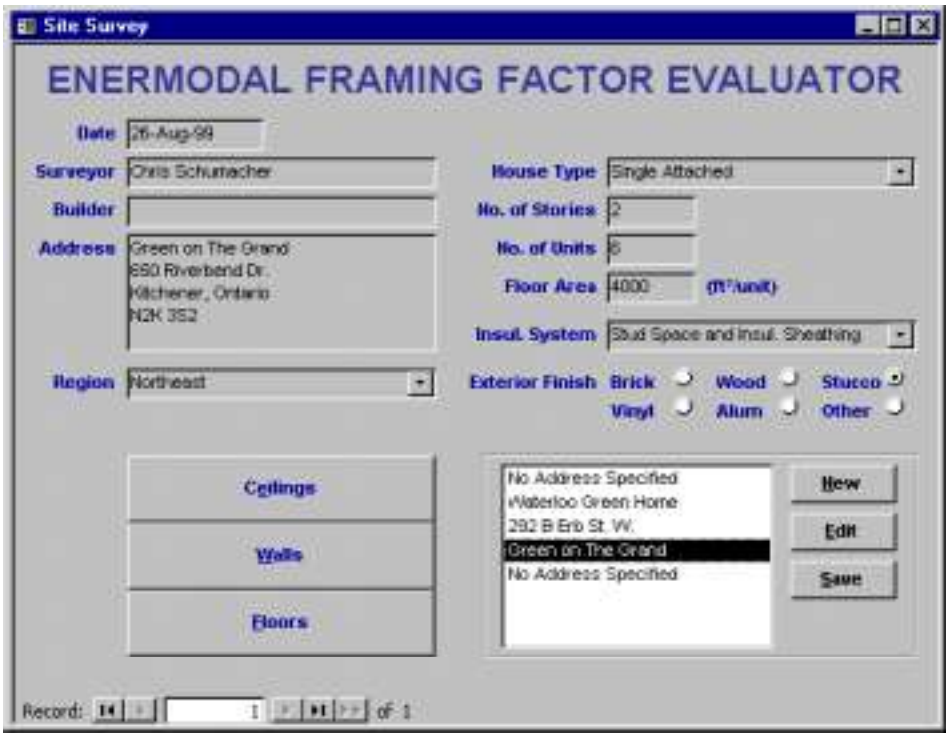


Figure I - 2: Site Survey Form

The program allows the surveyor to navigate through the survey site database using the "Site" list box. The surveyor can add a site by pressing the ***New*** button. When a new site is added, the surveyor is immediately asked to enter the general information for that site:

Date Enter the date on which the survey was conducted

Surveyor Enter the name of the surveyor

Builder Enter the name of the builder

Address Enter the address of the survey site

Zone Select the census zone of the survey site:
West, Midwest, Northeast, South

Dwelling Type Select the type of dwelling:
Single Detached, Single Attached, Multi-Family
If the building is Multi-Family, the surveyor should enter each unit type as a separate site. The sites are related using a similar address. Given a building with, for example, 8 units of one type of layout and 4 units of another, the surveyor would create two sites (e.g., Water St. A and Water St. B). One site would have 8 units and the other would have 4.

No. of Stories Enter the number of stories

No. of Units Enter the number of units if Multi-Family

Floor Area Enter the gross floor area in ft^2/unit

Insul. System Select the insulation placement used:
Cavity insulation, Insulating sheathing, Cavity & Insul. Sheathing

Exterior Finish Select the exterior wall finish(es) as applicable:
Brick, Wood, Stucco, Vinyl, Aluminum, Other

Once the general information has been entered, the database is updated by pressing the ***Save*** button. The surveyor can make corrections to the general information by selecting a site from the "Site" list box and pressing the ***Edit*** button. If necessary, the surveyor can remove a site from the database by selecting it from the "Site" list box and pressing the ***Delete*** button. All of the forms use similar list boxes to manage the database records.
The surveyor can enter or modify detailed site information by selecting a site from the "Site" list box and pressing one of the ***Ceilings***, ***Walls*** or ***Floors*** buttons. The detailed information forms are explained in the following sections.

Ceiling Form

The ***Ceiling*** form (Figure I - 3) allows the surveyor to enter detailed information about ceiling framing for each site. The information contained on the ***Ceiling*** form describes a ceiling element (i.e., a grouping of similar ceiling joists). A "Ceiling" list box allows the user to navigate through and edit ceiling elements.

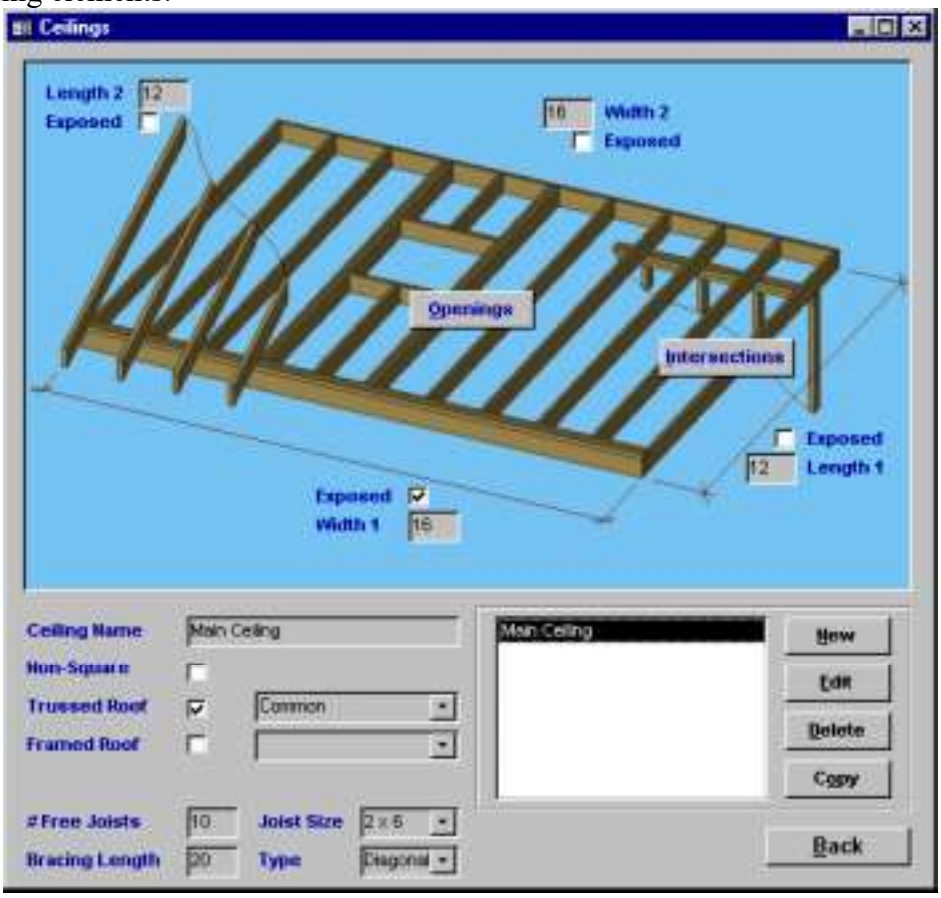


Figure I - 3: Ceiling Form

If the dwelling has more than a simple rectangular ceiling, the surveyor must enter the ceiling as several ceiling elements. The left of Figure I - 4 illustrates a complex ceiling. This ceiling can be entered as four ceiling elements (Figure I - 4 – right). Each element has three or four sides. A 3-sided element must have one right angle corner and a 4-sided element must have two right angle corners. The side of an element can be completely exposed to the exterior (e.g., a ring joist) or can be completely sheltered by another ceiling element. A side cannot be partially exposed and partially sheltered. In the example, ceiling element 2 has one exposed side while ceiling element 3 has three exposed sides. Ceiling elements 2 and 3 could not be combined into one element because one of the sides would be partially exposed and partially sheltered.

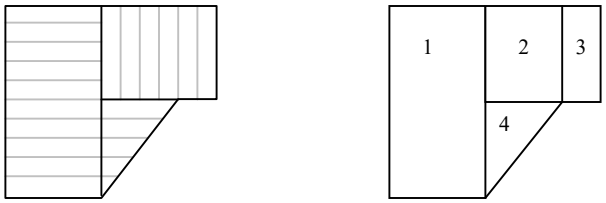


Figure I - 4: Dividing a Ceiling into Ceiling Elements

The surveyor can add a ceiling element by pressing the ***New*** button. When a new ceiling element is added, the surveyor is immediately asked to enter the details for that ceiling element.

Name Enter a name for the ceiling element

Non-square Check this box if the ceiling element is not rectangular

Length Enter the length of the ceiling element. The length is measured parallel to the span of the joists.

Width Enter the width of the ceiling element. The width is measured perpendicular to the span of the joists.

Exposed Check the exposed box on each side of the ceiling that is exposed to the exterior (i.e. a ring joist).

Trussed Roof Check this box if the ceiling is beneath a trussed roof, and select the type of truss used:
Common, Scissor, Raised Heel, Parallel, Cantilever, Dropped Chord

Framed Roof Check this box if the ceiling is beneath a framed roof, and select the type of bearing for the rafters & ceiling joists:
Vaulted, Top Plate, Rafter Plate

 # Free Joists Enter the number of free joists in the ceiling element. Free joists are joists that are NOT part of the framing around an opening and are NOT ring joists.

Joist Size Select the size of the joists used:
2 x 6, 2 x 8, 2 x 10, 2 x 12, 12 Wood-I, 14 Wood-I, 16 Wood-I

Bracing Length Enter the total length of the bracing. If there is more than one row of bracing, enter the sum of the lengths of the individual rows.

Bracing Select the type of bracing used:
Blocking, Cross Bracing, Let-In, Diagonal Bracing, Strapping

Once this information has been entered, the database is updated by pressing the ***Save*** button. The surveyor can make corrections to the information in a ceiling element by selecting it from the "Ceiling" list box and pressing the ***Edit*** button. If necessary, the surveyor can remove a ceiling element from the database by selecting it from the "Ceiling" list box and pressing the ***Delete*** button.
The surveyor must enter details about the ceiling openings and intersections. This is done in the forms accessed by the ***Openings*** and ***Intersections*** buttons.

Ceiling Openings Form

The ***Ceiling Openings*** (Figure I - 5) form is used to describe the framing around openings such as attic accesses and skylights. A "Ceiling Openings" list box is used to manage ceiling opening elements.

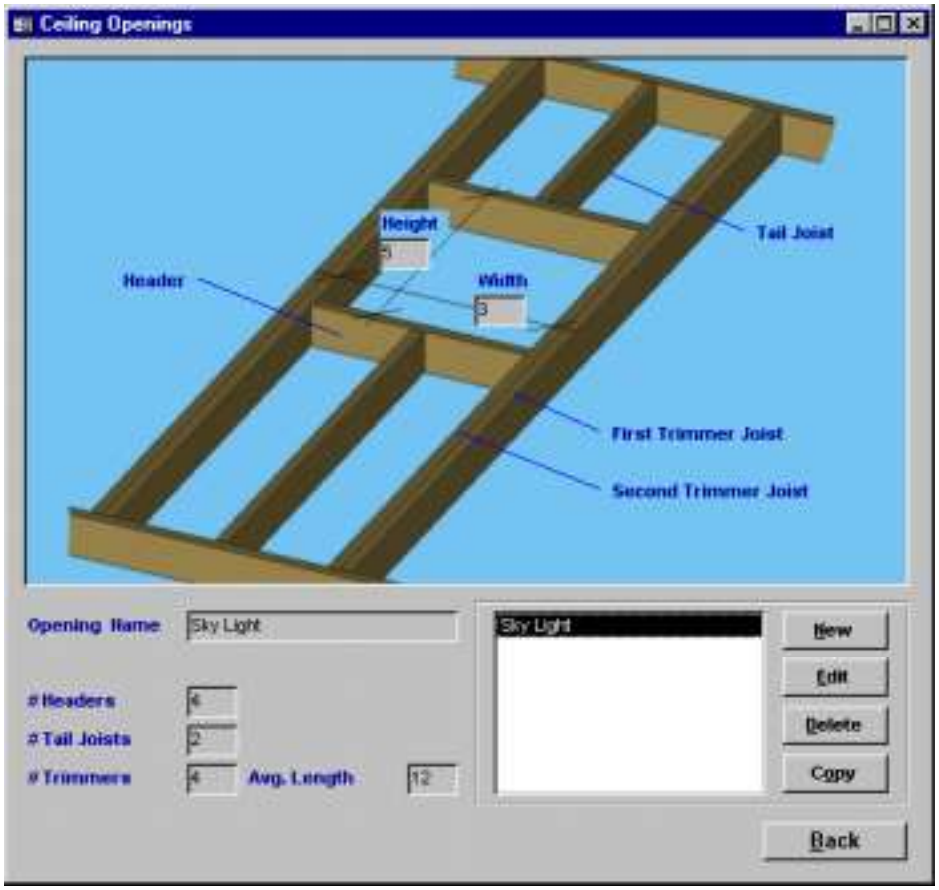


Figure I - 5: Ceiling Openings Form

Several details are necessary to describe each ceiling opening:

Name Enter a name for the ceiling opening.

Height Enter the height of the rough ceiling opening.

Width Enter the width of the rough ceiling opening.

 # Headers Enter the total number of headers included in the ceiling opening. Count all headers above and below the opening.

 # Tail Joists Enter the total number of tail joists included in the ceiling opening. Count all tail joists above and below the opening.

 # Trimmers Enter the total number of trimmer joists included in the ceiling opening. Count all trimmer joists on both sides of the opening.

Avg. Length Enter the average length of the trimmers.

Ceiling Intersections Form

The ***Ceiling Intersections*** (Figure I - 6) form is used to describe the framing at intersections between the ceiling elements and interior walls. The surveyor can manage the ceiling intersection elements using the "Ceiling Intersections" list box.

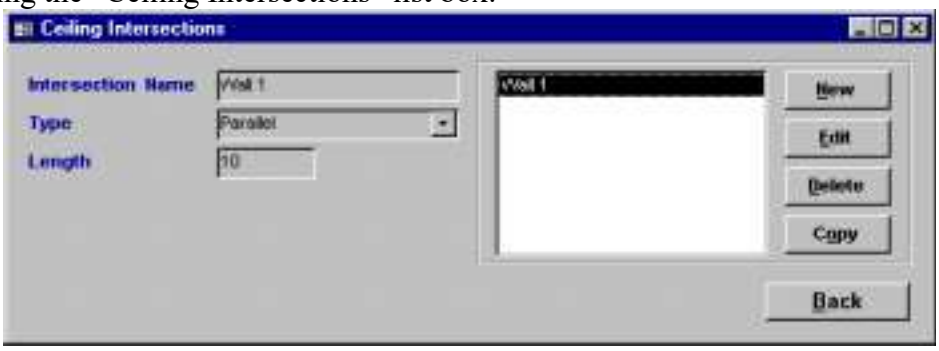


Figure I - 6: Ceiling Intersections Form

Few details are needed to describe a ceiling intersection:

Name Enter a name for the ceiling intersection.

Type Select the type of intersection:
Parallel (i.e., in the direction of the joists), Perpendicular

Length Enter the length of the intersection.

Wall Form

The ***Wall*** form (Figure I - 7) allows the surveyor to enter detailed information about wall framing for each site. The information contained on the ***Wall*** form describes a wall element (a grouping of similar wall studs). A "Wall" list box allows the user to navigate through and edit wall elements.

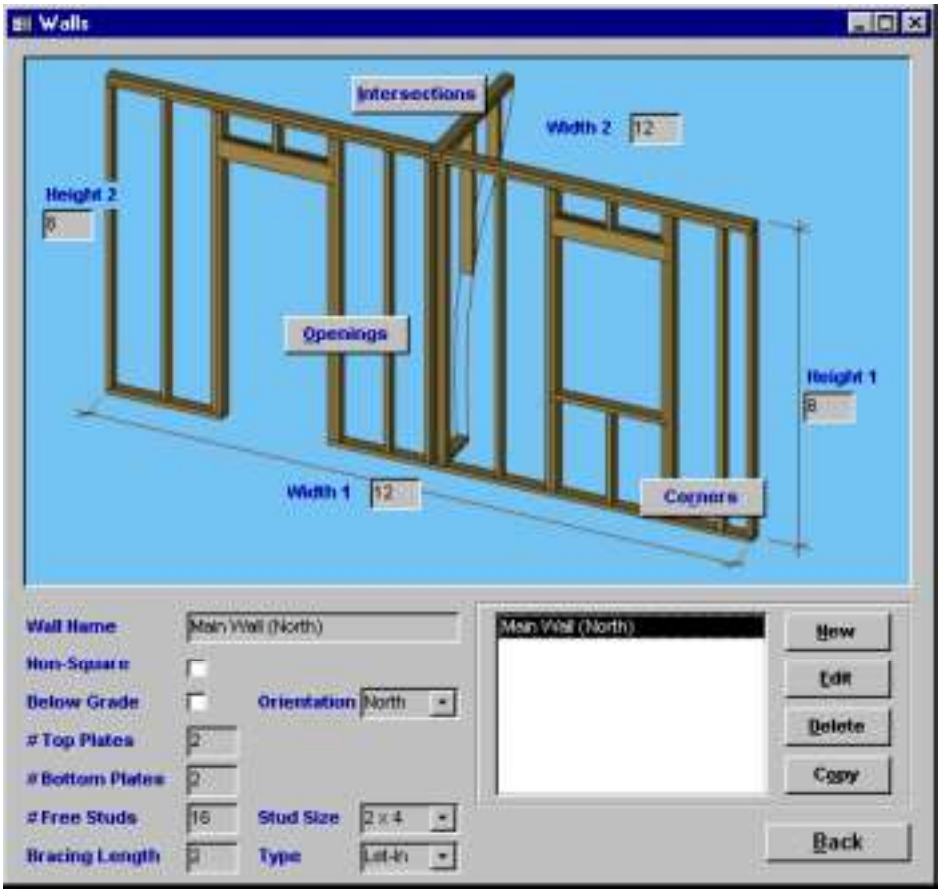


Figure I - 7: Wall Form

Like ceiling elements, wall elements can be 3- or 4-sided. However, since walls are more complicated than ceilings, more details are required to describe a wall element:

Name Enter a name for the wall element

Non-square Check this box if the wall element is not rectangular

Height Enter the height of the wall element. The height is measured parallel to the direction of the studs.

Width Enter the width of the wall element. The width is measured perpendicular to the direction of the studs.

Below Grade Check this box if the wall is below grade (i.e., a basement wall).

Orientation Select the orientation of the wall element:
N, NE, E, SE, S, SW, W, NW.

 # Top Plates Enter the number of top plates in the wall element.

 # Bottom Plates Enter the number of bottom plates in the wall element.

 # Free Studs Enter the number of free studs in the wall element. Free studs are studs that are NOT part of the framing around an opening or part of the framing at a corner.

Stud Size Select the size of the joists used:
2 x 4, 2 x 6

Bracing Length Enter the total length of the bracing in the wall element. If there is more than one row of bracing, enter the sum of the lengths of the individual rows.

Type Select the type of bracing used:
Blocking, Cross Bracing, Let-In, Diagonal Bracing, Strapping

The database is updated by pressing the ***Save*** button. The surveyor can make corrections to the information in a wall element by selecting it from the "Wall" list box and pressing the ***Edit*** button. If necessary, the surveyor can remove a wall element from the database by selecting it from the "Wall" list box and pressing the ***Delete*** button.
The surveyor must also enter details about the wall openings, intersections and corners. This is done in the forms accessed by the ***Openings, Intersections*** and ***Corners*** buttons.

Wall Openings Form

The ***Wall Openings*** (Figure I - 8) form is used to describe the framing around openings such as windows and doors. A "Wall Openings" list box is used to manage wall opening elements.

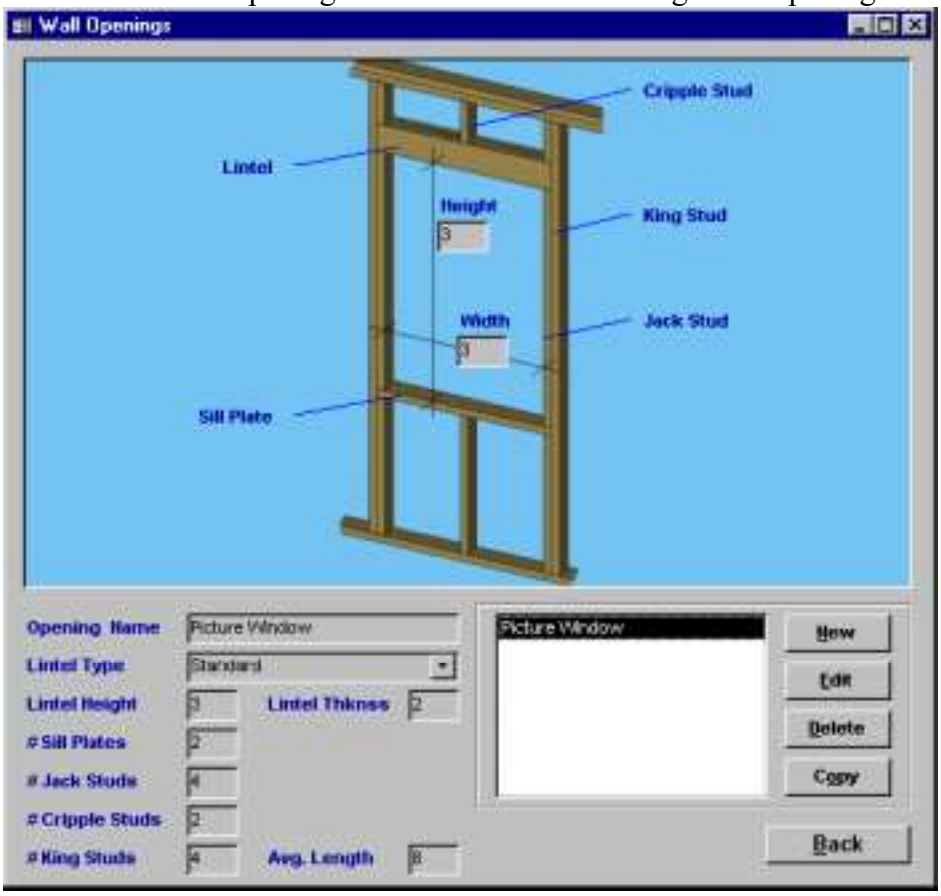


Figure I - 8: Wall Openings Form

Several details are necessary to describe each wall opening:

Name Enter a name for the wall opening.

Height Enter the height of the rough wall opening.

Width Enter the width of the rough wall opening.

Lintel Type Select the type of lintel used above the wall opening:
Single, Built-Up, Glu-Lam, Double, Double Insulated

Lintel Height Enter the total height of the lintel.

Lintel Thknss Enter the total thickness of the lintel (measured from inside to outside).

 # Sill Plates Enter the total number of sill plates at the bottom of the wall opening. If there are no sill plates, the opening is assumed to be a door, otherwise it is assumed to be a window.

 # Jack Studs Enter the total number of jack studs included in the wall opening. Count the jack studs on both sides of the opening.

 # Cripple Studs Enter the total number of cripple studs in the wall opening. Count all cripple studs above and below the opening.

 # King Studs Enter the total number of king studs included in the wall opening. Count the king studs on both sides of the opening.

Avg. Length Enter the average length of the king studs.

Wall Intersections Form

The ***Wall Intersections*** (Figure I - 9) form is used to describe the framing at intersections between the wall elements and interior walls. The surveyor can manage the wall intersection elements using the "Wall Intersections" list box.

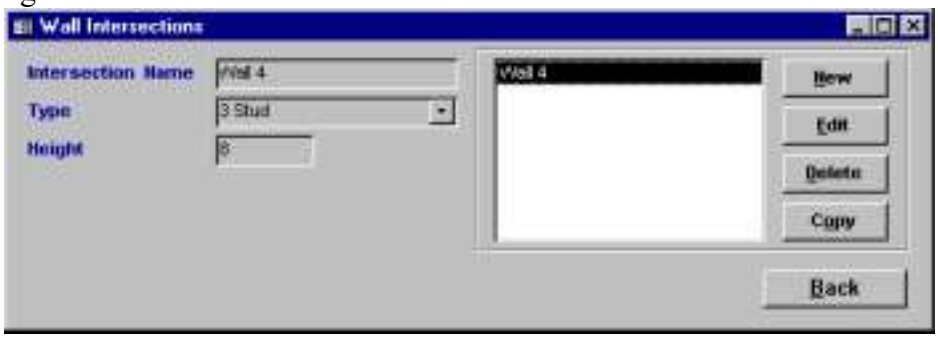


Figure I - 9: Wall Intersections Form

Few details are needed to describe a wall intersection:

Name Enter a name for the wall intersection.

Type Select the type of intersection:
3 Stud, 2 Stud, 1 Stud w/ blocking, 1 Stud w/ clips

Length Enter the length of the intersection.

Floor Form

The ***Floor*** form (Figure I - 10) allows the surveyor to enter detailed information about floor framing for each site. The information contained on the ***Floor*** form describes a floor element (a grouping of similar floor joists). A "Floor" list box allows the user to navigate through and edit floor elements.

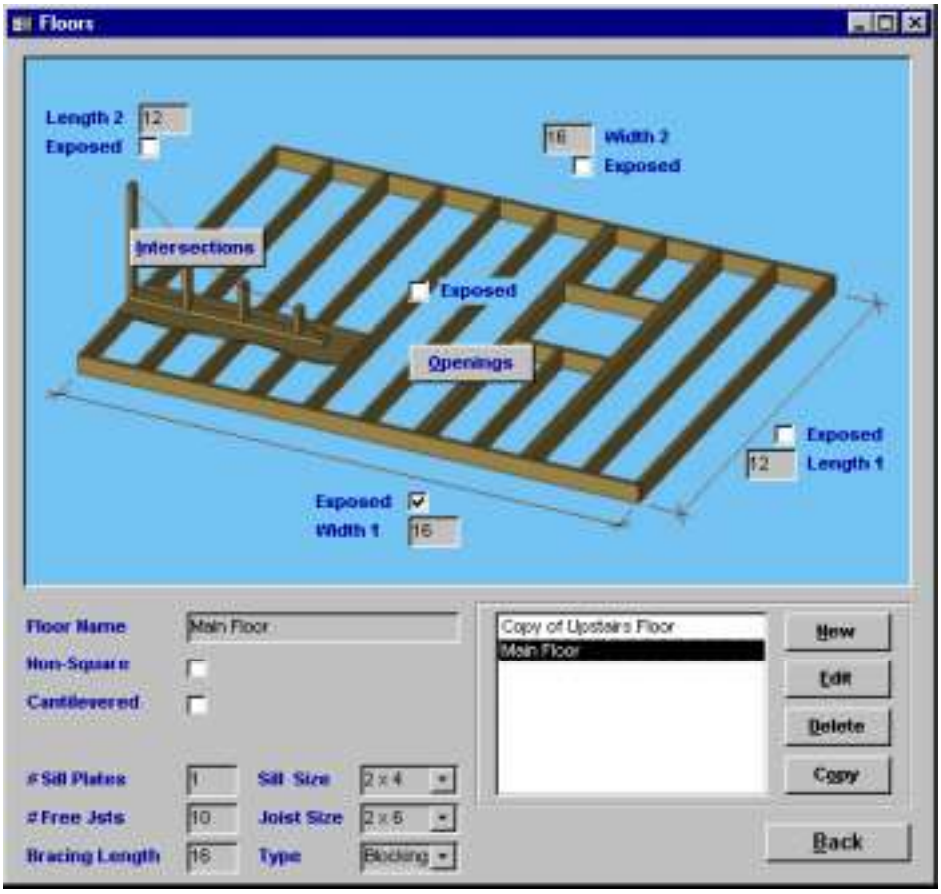


Figure I - 10: Floor Form

Like ceiling elements and wall elements, floor elements can be 3- or 4-sided. Different information is required to describe a floor element:

Name Enter a name for the floor element.

Non-square Check this box if the floor element is not rectangular.

Cantilevered Check this box if the floor element is cantilevered past the edge of the element that supports it.

Length Enter the length of the wall element. The length is measured parallel to the direction of the joists.

Width	Enter the width of the floor element. The width is measured perpendicular to the direction of the joists.
# Sill Plates	Enter the number of sill plates if the floor is supported by a foundation wall.
Sill Size	Select the size of the sill plate used: *2 x 4, 2 x 6, 2 x 8*
# Free Joists	Enter the number of free joists in the ceiling element. Free joists are joists that are NOT ring joists or part of the framing around an opening.
Joist Size	Select the size of the joists used: *2 x 6, 2 x 8, 2 x 10, 2 x 12, 12 Wood-I, 14 Wood-I, 16 Wood-I*
Bracing Length	Enter the total length of the bracing in the floor element. If there is more than one row of bracing, enter the sum of the lengths of the individual rows.
Type	Select the type of bracing used: *Blocking, Cross Bracing, Let-In, Diagonal Bracing, Strapping*

The database is updated by pressing the ***Save*** button. The surveyor can make corrections to the information in a floor element by selecting it from the "Floor" list box and pressing the ***Edit*** button. If necessary, the surveyor can remove a floor element from the database by selecting it from the "Floor" list box and pressing the ***Delete*** button.
The surveyor must also enter details about the floor openings and intersections. This is done in the forms accessed by the ***Openings*** and ***Intersections*** buttons.

Floor Openings Form

The ***Floor Openings*** (Figure I - 11) form is used to describe the framing around openings such as crawlspace accesses. A "Floor Openings" list box is used to manage floor opening elements.

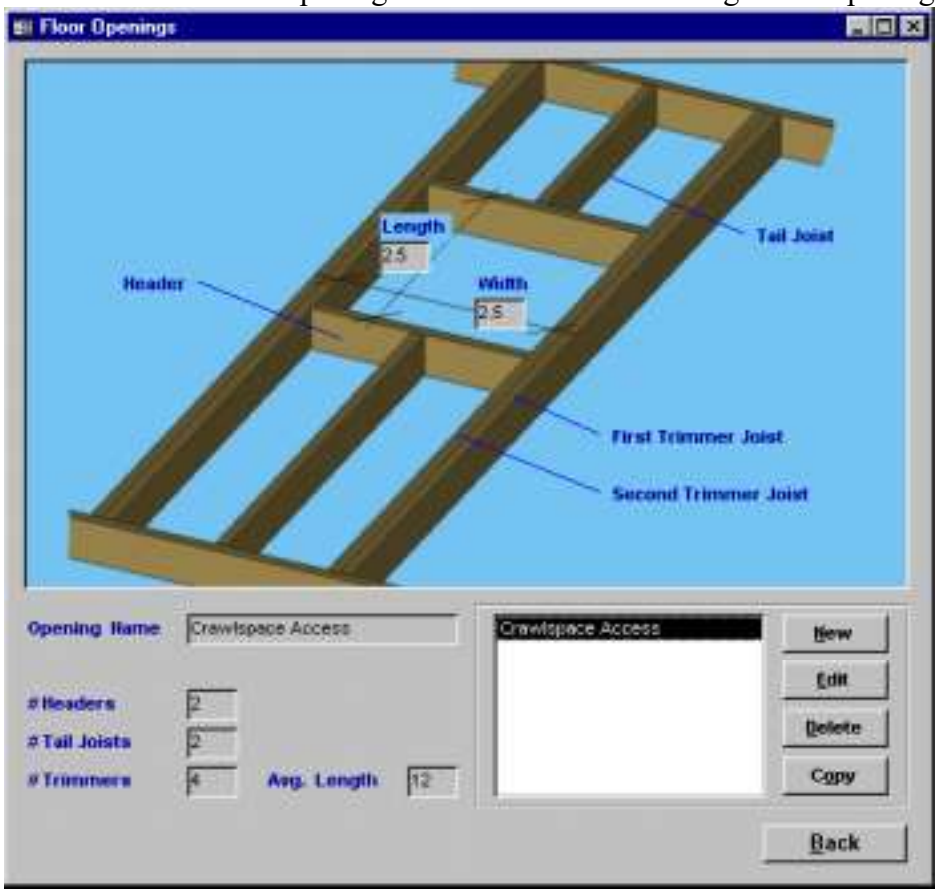


Figure I - 11: Floor Openings Form

Several details are necessary to describe each floor opening:

Name Enter a name for the floor opening.

Length Enter the length of the rough floor opening.

Width Enter the width of the rough floor opening.

 # Headers Enter the total number of headers included in the floor opening. Count all headers on both ends of the opening.

 # Tail Joists Enter the total number of tail joists included in the floor opening. Count all tail joists on both ends of the opening.

 # Trimmers Enter the total number of trimmer joists included in the floor opening. Count all trimmer joists on both sides of the opening.

Avg. Length Enter the average length of the trimmers.

Floor Intersections Form

The ***Floor Intersections*** (Figure I - 12) form is used to describe the framing at intersections between the ceiling elements and interior walls. The surveyor can manage the ceiling intersection elements using the "Ceiling Intersections" list box.

Figure I - 12: Floor Intersections Form

Few details are needed to describe a floor intersection:

Name Enter a name for the floor intersection.

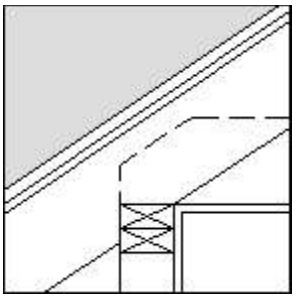
Type Select the type of intersection:
Parallel (i.e., in the direction of the joists), Perpendicular

Length Enter the length of the intersection.

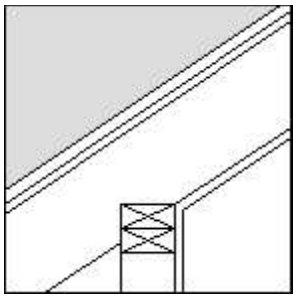
Typical Framing Details

Figure I - 13 illustrates the choices available for the Framed Roof (Section 0), Corners (Section 0), Ceiling Intersections (Section 0) and Wall Intersections (Section 0) list boxes.

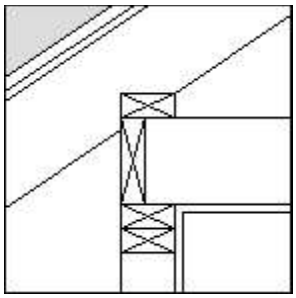
Framed Roofs @ Eave



Double Top Plate

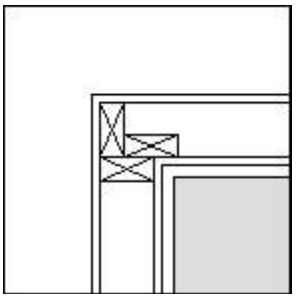


Vaulted

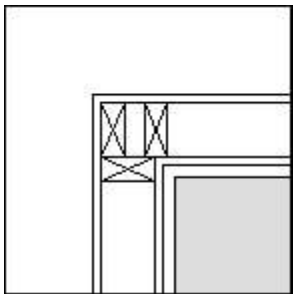


Rafter Plate

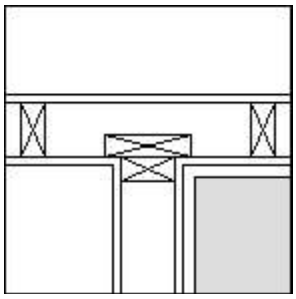
Inside Corners



3-Stud A

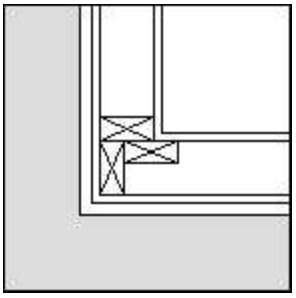


3-Stud B

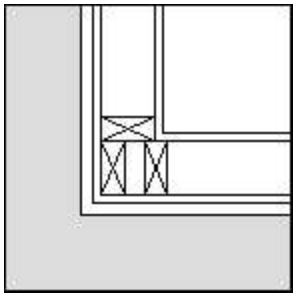


2-Stud

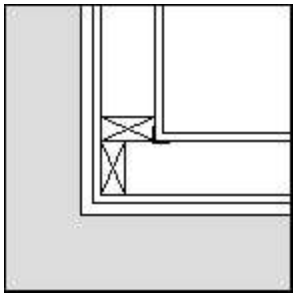
Outside Corners



3-Stud A

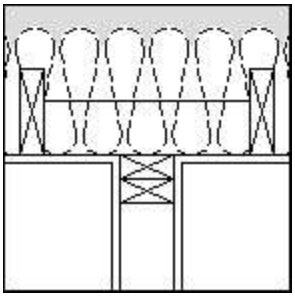


3-Stud B

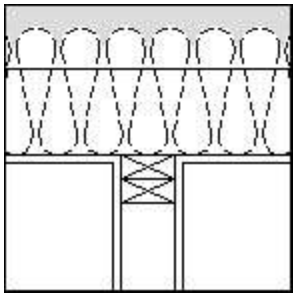


2-Stud w/ Clips

Ceiling/Wall Intersections

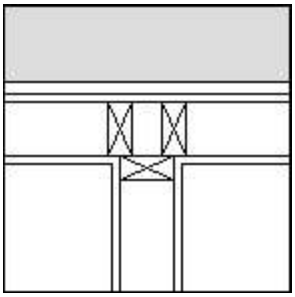


Parallel

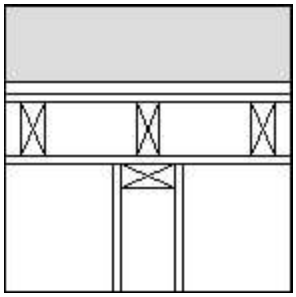


Perpendicular

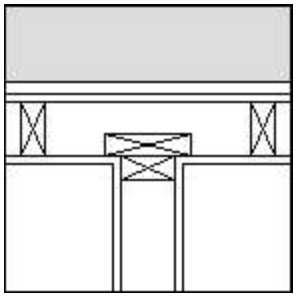
Wall/Wall Intersections



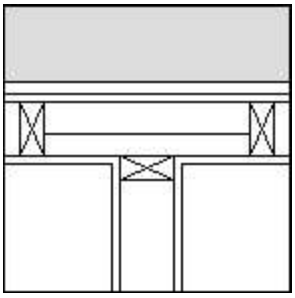
3-Stud



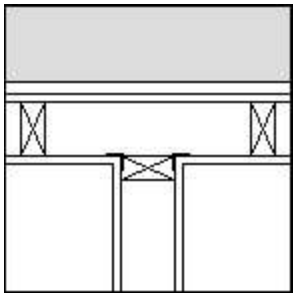
2-Stud A



2-Stud B



1-Stud w/ Blocking



1-Stud w/ Clips

Figure I - 13: Typical Framing Details

Appendix II – Audit Results for Individual Dwellings

Summary of Data - Detached Dwellings

						Framing Factors -- GROSS				Framing Factors -- NET				Ratios					
Code	Zone	Basement	House	Notes	Floor Area	Ceiling F.F.	Wall F.F.	Floor F.F.	Overall F.F.	Ceiling F.F.	Wall F.F.	Floor F.F.	Overall F.F.	Window to Wall Area	Door to Wall Area	Corner Right to Wall Area	Exp Perim to Wall Area	Ceiling Opening to Ceiling	Floor Opening to Floor Area
05	3	slab	one story	0	2517	7.2	21.3	0.0	12.0	7.2	27.5	0.0	14.1	14.7	7.9	0.4	0.00	0.0	0.0
06	3	slab	one story	0	2433	7.4	24.5	0.0	10.6	7.5	30.0	0.0	11.6	13.7	4.8	0.4	0.00	0.2	0.0
07	3	slab	one story	0	1595	8.6	21.5	0.0	11.6	8.6	25.9	0.0	12.6	9.9	7.3	0.4	0.00	0.4	0.0
08	3	slab	one story	0	1659	6.6	19.5	0.0	9.3	6.5	23.2	0.0	10.1	10.0	6.3	0.4	0.00	0.3	0.0
013	3	slab	one story	0	2418	10.6	30.0	0.0	12.9	10.6	36.1	0.0	14.4	9.8	13.6	0.6	0.00	0.0	0.0
016	3	slab	one story	0	1872	7.1	20.6	0.0	10.8	7.1	24.4	0.0	11.8	11.1	4.7	0.8	0.00	0.3	0.0
017	3	slab	one story	0	1973	8.7	19.9	0.0	10.6	8.7	24.2	0.0	11.9	10.1	7.8	0.8	0.00	0.0	0.0
018	3	slab	one story	0	2251	6.5	24.1	0.0	11.3	6.5	29.2	0.0	12.7	13.7	3.8	0.6	0.00	0.2	0.0
019	3	slab	two story	0	3873	5.7	35.6	0.0	11.7	5.7	30.3	0.0	13.1	12.8	2.9	0.6	0.00	0.0	0.0
020	3	slab	one story	0	1684	5.4	25.4	0.0	13.6	5.4	32.5	0.0	16.5	16.1	5.7	0.4	0.00	0.0	0.0
021	3	slab	two story	0	2519	7.4	23.5	0.0	14.1	7.5	30.1	0.0	16.9	18.5	3.2	0.4	0.53	0.6	0.0
01	4	slab	two story	0	3555	7.7	30.7	0.0	12.3	7.7	25.6	0.0	14.0	13.9	5.4	0.4	0.64	0.5	0.0
02	4	slab	one story	0	1981	7.5	32.5	0.0	10.2	7.5	28.0	0.0	11.3	13.3	6.5	0.6	0.00	0.3	0.0
03	4	slab	one story	0	2357	8.7	21.4	0.0	9.9	8.7	25.4	0.0	11.0	15.2	3.9	0.4	0.00	0.4	0.0
04	4	slab	two story	0	3984	8.6	32.2	0.0	11.8	8.6	27.7	0.0	13.7	16.0	3.9	0.8	0.15	0.6	0.0
09	4	slab	two story	0	1315	7.0	22.3	0.0	16.2	7.0	25.7	0.0	18.3	9.4	4.1	0.8	0.62	0.6	0.0
010	4	slab	two story	0	1467	8.6	32.2	0.0	13.3	8.6	25.7	0.0	14.8	9.4	4.0	0.6	0.51	0.5	0.0
011	4	slab	two story	0	2536	7.0	30.6	0.0	10.2	7.0	23.9	0.0	11.7	10.9	2.8	0.4	0.21	0.4	0.0
012	4	slab	two story	0	1983	5.4	19.6	0.0	10.7	5.4	22.7	0.0	11.9	8.9	5.0	0.4	0.17	0.0	0.0
014	4	slab	two story	0	3043	6.2	32.3	0.0	11.1	6.2	26.1	0.0	12.3	10.9	3.6	0.5	0.40	0.5	0.0
015	4	slab	two story	0	1536	7.0	21.5	0.0	13.9	7.0	24.9	0.0	15.5	10.4	3.0	0.6	0.33	0.0	0.0
022	4	slab	one story	0	1271	6.5	17.0	0.0	9.8	6.5	19.3	0.0	10.5	6.4	5.5	0.4	0.00	0.4	0.0
023	4	slab	one story	0	1483	7.1	19.0	0.0	9.5	7.1	22.3	0.0	10.2	6.7	8.1	0.5	0.00	0.3	0.0
024	4	slab	one story	0	1830	7.1	20.3	0.0	9.6	7.1	23.0	0.0	10.2	6.9	4.7	0.4	0.00	0.3	0.0
025	4	slab	one story	0	2068	6.9	20.6	0.0	9.6	6.9	24.4	0.0	10.3	7.7	6.8	0.4	0.00	0.2	0.0
026	4	slab	one story	0	1257	6.7	18.3	0.0	8.8	6.7	21.0	0.0	9.3	8.0	5.0	0.3	0.00	0.3	0.0
027	4	slab	one story	0	1859	5.6	18.7	0.0	10.0	5.6	21.1	0.0	10.8	6.6	4.8	0.4	0.44	0.0	0.0
028	4	slab	two story	0	3529	7.3	32.8	0.0	12.9	7.3	27.3	0.0	14.6	13.2	3.2	0.4	0.52	0.3	0.0
029	4	slab	two story	0	3548	6.7	24.1	0.0	14.0	6.7	31.8	0.0	17.2	21.5	2.6	0.4	0.15	0.3	0.0
030	4	slab	two story	0	3625	6.3	25.0	0.0	14.3	6.3	31.7	0.0	17.2	18.2	3.0	0.6	0.24	0.0	0.0
			Averages:		**Overall**	**6.9**	**21.6**	**0.0**	**11.6**	**6.9**	**26.1**	**0.0**	**13.0**	**11.8**	**5.1**	**0.5**	**0.38**	**0.4**	**0.0**
					Zone 3	**7.2**	**22.3**	**0.0**	**11.7**	**7.2**	**27.6**	**0.0**	**13.3**	**12.8**	**6.2**	**0.5**	**0.53**	**0.3**	**0.0**
					Zone 4	**6.7**	**21.1**	**0.0**	**11.5**	**6.7**	**25.2**	**0.0**	**12.9**	**11.2**	**4.5**	**0.5**	**0.36**	**0.4**	**0.0**
			Standard Deviations:		**Overall**	**0.9**	**2.1**	**0.0**	**1.8**	**0.9**	**3.3**	**0.0**	**2.5**	**3.8**	**2.2**	**0.1**	**0.2**	**0.2**	**0.0**
					Zone 3	**1.4**	**2.2**	**0.0**	**1.6**	**1.4**	**2.9**	**0.0**	**2.2**	**2.8**	**3.0**	**0.2**	**0.2**	**0.2**	**0.0**
					Zone 4	**0.5**	**2.8**	**0.0**	**2.0**	**0.5**	**3.3**	**0.0**	**2.7**	**4.1**	**1.4**	**0.1**	**0.2**	**0.2**	**0.0**

Summary of Data - Attached Dwellings

						Framing Factors -- GROSS				Framing Factors – Net				Ratios					
Code	Zone	Basement	House	Notes	Floor Area	Ceiling F.F. (Gross)	Wall F.F. NEW	Floor F.F. Gross	Overall F.F. NEW	Ceiling F.F.	Wall F.F.	Floor F.F.	Overall F.F.	Window to Wall Area	Door to Wall Area	Corner Right to Wall Area	Exp Perim to Wall Area	Ceiling Opening to Ceiling Area	Floor Opening to Floor Area
A8	3	slab	one story	0	1642	6.9	17.6	0.0	9.7	6.9	22.2	0.0	11.0	11.8	9.1	0.6	0.00	0.4	0.0
A9	3	slab	one story	0	1642	6.9	18.4	0.0	9.0	7.0	23.5	0.0	10.0	12.5	9.0	0.9	0.00	0.4	0.0
A1	4	slab	two story	0	1792	8.6	24.4	0.0	13.1	8.7	30.6	0.0	14.9	14.7	5.5	0.8	0.25	0.5	0.0
A2	4	slab	two story	0	2158	6.7	23.3	0.0	10.0	6.7	29.6	0.0	11.3	16.1	5.4	0.7	0.29	0.6	0.0
A3	4	slab	two story	0	1767	7.6	23.0	0.0	11.6	7.6	31.4	0.0	13.7	15.5	11.3	0.8	0.23	0.0	0.0
A4	4	slab	two story	0	1672	7.8	21.7	0.0	12.6	7.9	25.4	0.0	13.9	8.9	5.7	0.8	0.19	0.5	0.0
A5	4	slab	two story	0	1678	6.5	20.7	0.0	9.4	6.5	24.0	0.0	10.1	7.6	6.2	0.7	0.34	0.0	0.0
A6	4	slab	two story	0	1600	6.8	22.3	0.0	10.2	6.8	26.9	0.0	11.0	7.6	6.2	0.8	0.31	0.0	0.0
A7	4	slab	two story	0	1344	6.6	20.4	0.0	11.6	6.6	23.7	0.0	12.7	10.0	3.8	0.7	0.00	0.0	0.0
A10	4	slab	two story	0	1216	9.2	21.3	0.0	15.8	9.3	25.1	0.0	17.9	12.3	2.8	0.6	0.21	0.8	0.0
A11	4	slab	two story	garage under	1584	6.6	22.0	0.0	14.8	6.6	27.7	0.0	17.9	6.6	14.7	1.3	0.16	0.6	0.0
A12	4	slab	two story	garage under	1259	7.6	21.5	0.0	13.5	7.7	25.7	0.0	15.4	10.3	6.2	1.6	0.45	0.7	0.0
A13	4	slab	one story	0	1039	9.9	22.2	0.0	16.9	9.9	26.3	0.0	19.3	11.2	4.4	0.4	0.23	0.5	0.0
A14	4	slab	two story	0	1131	6.9	21.9	0.0	12.2	7.0	27.8	0.0	14.3	12.5	8.6	0.9	0.20	0.8	0.0
A15	4	slab	two story	0	1368	6.4	20.4	0.0	11.8	6.4	25.1	0.0	13.6	12.6	6.1	0.8	0.16	0.6	0.0
A16	4	slab	two story	0	1471	6.9	23.5	0.0	10.1	6.9	31.7	0.0	12.1	19.0	7.0	0.9	0.23	0.6	0.0
A17	4	slab	two story	0	1786	6.1	21.0	0.0	8.9	6.1	26.3	0.0	9.9	14.2	6.8	1.1	0.16	0.5	0.0
A18	4	slab	two story	0	1141	9.3	22.6	0.0	19.0	9.4	28.0	0.0	23.0	12.6	6.6	0.8	0.38	0.6	0.0
			Averages:		**Overall**	**7.3**	**21.6**	**0.0**	**12.2**	**7.4**	**26.7**	**0.0**	**14.0**	**12.0**	**6.9**	**0.8**	**0.24**	**0.6**	**0.0**
					Zone 3	**6.9**	**18.0**	**0.0**	**9.4**	**6.9**	**22.8**	**0.0**	**10.5**	**12.1**	**9.0**	**0.7**	**0.00**	**0.4**	**0.0**
					Zone 4	**7.4**	**22.0**	**0.0**	**12.6**	**7.4**	**27.1**	**0.0**	**14.4**	**12.0**	**6.6**	**0.8**	**0.24**	**0.6**	**0.0**
			Standard Deviations:		**Overall**	**1.1**	**1.3**	**0.0**	**2.8**	**1.1**	**2.4**	**0.0**	**3.5**	**3.2**	**2.7**	**0.3**	**0.1**	**0.3**	**0.0**
					Zone 3	**0.7**	**0.2**	**0.0**	**1.1**	**0.7**	**1.3**	**0.0**	**1.7**	**0.4**	**4.2**	**0.1**	**0.0**	**0.4**	**0.0**
					Zone 4	**1.2**	**1.2**	**0.0**	**2.9**	**1.2**	**2.1**	**0.0**	**3.6**	**3.1**	**2.6**	**0.3**	**0.1**	**0.3**	**0.0**

Summary of Data - Multi-family Dwellings

						Framing Factors -- GROSS				Framing Factors -- Net				Ratios					
Code	Zone	Basement	House	Notes	Floor Area/Unit	Ceiling F.F. (Gross)	Wall F.F. (Gross)	Floor F.F. Gross	Overall F.F. (Gross)	Ceiling F.F.	Wall F.F.	Floor F.F.	Overall F.F.	Window to Wall Area	Door to Wall Area	Corner Hght to Wall Area	Exp Perim to Wall Area	Ceiling Opening to Ceiling Area	Floor Opening to Floor Area
M2	3	slab	2 story	2/8 units	1119	8.3	21.0	0.0	18.9	8.2	25.4	0.0	19.6	10.7	6.3	0.7	0.92	0.4	0.0
M3	3	slab	3 story	5/20 units	4861	8.1	20.8	0.0	16.7	8.2	24.8	0.0	19.5	10.9	5.3	0.7	0.66	0.4	0.0
M7	3	slab	3 story	5/20 units	693	3.0	21.6	0.0	17.7	7.2	27.7	0.0	23.4	9.9	12.1	1.0	0.36	0.1	0.0
M8	3	slab	2 story	4/16 units	961	7.4	19.6	0.0	16.2	7.4	23.7	0.0	17.9	6.7	8.5	1.0	0.88	0.0	0.0
M1	4	slab	2 story	4/16 units	938	6.7	20.3	0.0	15.4	6.7	23.9	0.0	17.7	4.2	10.4	0.6	0.57	0.0	0.0
M4	4	slab	2 story	4/16 units	870	5.9	19.8	0.0	14.9	6.9	26.1	0.0	18.9	15.9	8.1	0.8	0.50	0.5	0.0
M5	4	slab	2 story	4/8 units	1156	8.3	20.4	0.0	14.3	8.1	28.8	0.0	19.6	21.2	7.0	0.9	0.21	0.6	0.0
M6	4	slab	3 story	6/24 units	1140	2.3	22.9	0.0	18.8	6.8	29.9	0.0	25.3	13.4	9.8	1.2	0.60	0.0	0.0
M9	4	slab	3 story	5/32 units	904	8.0	21.6	0.0	16.6	7.6	28.7	0.0	19.8	9.0	14.5	1.0	0.51	0.0	0.0
M10	4	slab	3 story	4/7 units	966	6.9	23.0	0.0	20.5	6.9	28.6	0.0	25.3	10.8	9.8	0.9	0.64	0.5	0.0
M11	4	slab	3 story	6/24 units	1052	12.7	22.0	0.0	20.0	12.7	26.5	0.0	23.5	4.7	12.1	0.9	0.76	0.0	0.0
M12	4	slab	2 story	6/24 units	790	7.2	23.5	0.0	19.7	2.4	32.4	0.0	25.4	10.0	17.4	1.1	0.48	0.0	0.0
			Averages:		**Overall**	**6.9**	**21.4**	**0.0**	**17.2**	**6.7**	**27.2**	**0.0**	**21.2**	**10.8**	**10.1**	**0.9**	**0.59**	**0.4**	**0.0**
					Zone 3	**6.7**	**20.7**	**0.0**	**16.6**	**6.7**	**25.4**	**0.0**	**19.8**	**10.0**	**8.1**	**0.9**	**0.71**	**0.3**	**0.0**
					Zone 4	**7.0**	**21.7**	**0.0**	**17.5**	**6.6**	**28.1**	**0.0**	**21.9**	**11.1**	**11.1**	**0.9**	**0.54**	**0.5**	**0.0**
			Standard Deviations:		**Overall**	**2.3**	**1.3**	**0.0**	**2.1**	**2.5**	**2.5**	**0.0**	**2.9**	**4.6**	**2.9**	**0.2**	**0.2**	**0.3**	**0.0**
					Zone 3	**0.6**	**0.4**	**0.0**	**0.5**	**0.9**	**2.3**	**0.0**	**0.9**	**7.5**	**1.4**	**0.2**	**0.3**	**0.3**	**0.0**
					Zone 4	**2.8**	**0.9**	**0.0**	**1.9**	**3.0**	**2.2**	**0.0**	**2.4**	**2.3**	**3.0**	**0.1**	**0.1**	**0.2**	**0.0**

Floor Area Distribution for Survey Site Selection Criteria

Table 3 and Table 4 illustrate the distribution of houses constructed in the Western Census region in 1999 (based on floor area). The data used for these figures were adapted from the US Census Bureau reports on the "Characteristics of New Housing". This data can be easily accessed at http://www.census.gov/const/www/charindex.html. Data is currently available for the years 1994 through 2000. For convenience, the data for 1999 has been reproduced in the following table:

Table II - 1: U.S. Census Bureau Data for Distribution of Dwellings by Floor Area – Western Census Region

Single-Family Dwellings			Multi-Family Dwellings		
	Number of Units	Percent Distribution		Number of Units	Percent Distribution
Under 1,200 ft²	17,000	5	Under 600 ft²	1,000	0
1,200 to 1,599	62,000	20	600 to 799	11,000	4
1,600 to 1,999	74,000	24	800 to 999	27,000	9
2,000 to 2,399	53,000	17	1,000 to 1,199	23,000	7
2,400 to 2,999	52,000	17	1,200 plus	22,000	7
3,000 plus	51,000	16			
Total	310,000	100	Total	85,000	27

Geographic Distribution for Survey Site Selection Criteria

Table 5 and Table 6Table II - 2 illustrate the geographic distribution of housing starts in the State of California in 1999 (based on permits issued). The data sources for these figures are the U.S. Bureau of Census and the Real Estate Center at Texas A&M University. Table II - 2 shows the housing starts for California Metropolitan Statistical Areas (MSAs). Table II - 3 summarizes the data in Table II - 2 on the basis of zone and dwelling type (i.e. single- or multi-family). The distribution shown in Table II -3 was used as the basis for establishing the geographic distribution of survey sites shown in Table II - 4.

Table II - 2: Summary of Housing Start Data for Selected MSAs in the State of California

Metropolitan Statistical Area	Counties Included	Map ID	Location latitude	Location longitude	seismic zone	Housing Starts (1000s) single family	Housing Starts (1000s) multi-family	Dot size on Map	
Bakersfield	Kern	1	35.42	119.05	4	2.89	0.23	4.5	
Fresno	Fresno, Madera	2	36.77	119.72	3	3.09	0.49	4.8	
Los Angeles	Los Angeles	3	33.93	118.40	4	7.83	6.23	9.5	
Oakland	Alameda,Contra Costa	4	37.82	122.32	4	8.85	1.96	8.3	
Orange County	Orange	5	33.00	117.00	4	7.68	4.56	8.9	
Riverside	Riverside, San Bernardino	6	33.90	117.25	4	19.02	1.9	11.6	
Sacramento	Sacramento, Placer, El Dorado	7	38.52	121.50	3	10.28	2.74	9.2	
Salinas	Monterey	8	36.67	121.60	4	1.48	0.57	3.6	
San Diego	San Diego	9	32.73	117.17	4	10.07	6.23	10.2	
San Francisco	San Francisco, San Mateo, Marin	10	37.62	122.38	4	1.66	2.73	5.3	
San Jose	Santa Clara	11	37.37	121.93	4	3.32	3.56	6.7	
Santa Barbara	Santa Barbara	12	34.43	119.83	4	0.62	0.19	2.3	
Santa Rosa	Sonoma	13	38.52	122.82	4	2.35	0.69	4.4	
Stockton	San Joaquin	14	37.90	121.25	3	4.19	0.01	5.2	
Vallejo	Solano, Napa	15	38.00	122.00	4	2.08	0.64	4.2	
Ventura	Ventura	16	34.00	119.00	4	3.64	0.78	5.3	
Visalia	Tulare	17	36.33	119.30	3	1.54	0.1	3.3	
						90.59	33.61	800	Mag
						73%	27%	0.5	Exp

Table II - 3: Percent Distribution of Starts for CA

		single family	multi-family	%
Zone Total	4	71.49	30.27	82%
	3	19.1	3.34	18%
Zone %	4	58%	24%	
	3	15%	3%	

Table II - 4: Distribution of Starts for Site Selection

Distribution of Sites for California Survey			
Total Sites	60	Zone 3	Zone 4
	Detached	8	22
	Attached	6	12
	Multi	4	8
		18	42

Floor Area Distribution of the Sites Surveyed

Upon initially receiving the results from the survey, one of the reviewers noted that none of the floor areas of the detached dwellings used in the California study were over 3000 square feet. The reviewer suggested that there has been a trend to larger dwellings and asked how the distribution of the floor areas compared to the published statistics.

In response, a spreadsheet (Figure II - 1) was prepared to compare the distribution of the floor areas from the California survey to the statistics for the Western census region (data from the US Census Bureau). The results show that the survey data is lacking in dwellings over 3000 sq. ft., but makes up for it in the 2400 to 2999 sq. ft. range. Furthermore, four of the dwellings are over 2800 sq. ft. in floor area, so it is likely that the data is representative of the general housing stock in the state of California.

California Detached Houses Floor Area		Categories	Code	Count	CA Sample	US Census Bureau Western Census Data
1271	b	under 1200	a	0	0%	8%
1315	b	1200 to 1599	b	7	23%	21%
1357	b	1600 to 1999	c	8	27%	22%
1467	b	2000 to 2399	d	5	17%	17%
1483	b	2400 to 2999	e	10	33%	16%
1536	b	3000 plus	f	0	0%	16%
1595	b			30	100%	100%
1659	c					
1684	c					
1830	c					
1859	c					
1872	c					
1973	c					
1981	c					
1983	c					
2043	d					
2068	d					
2251	d					
2326	d					
2357	d					
2418	e					
2433	e					
2517	e					
2519	e					
2548	e					
2555	e					
2825	e					
2829	e					
2873	e					
2984	e					

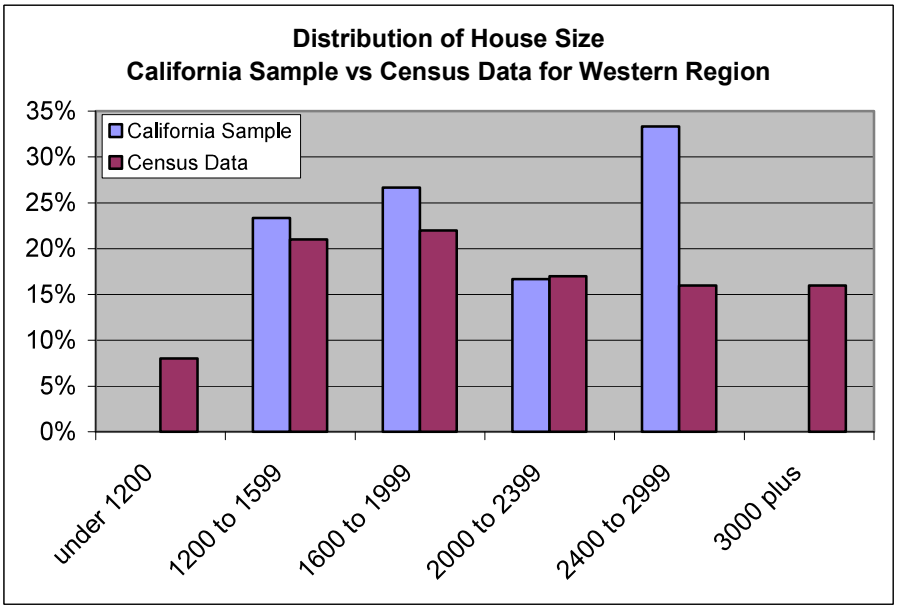


Figure II - 1: California Survey Floor Areas vs. US Census Bureau Western Region Floor Areas

Statistical Calculations

The means, standard deviations, confidence intervals and correlation coefficients quoted throughout the report were calculated using the statistical functions built into Microsoft Excel 2000. The tables used to calculate these values follow.

Mean $= \bar{x} = \frac{\sum_i x}{n}$ where n = number of samples x_i = parameter value for sample i	Correlation Coefficient $= \rho_{x,y} = \frac{\mathrm{Cov}(X,Y)}{\sigma_x \cdot \sigma_y}$ where $-1 \le \rho_{x,y} \le 1$ $\mathrm{Cov}(X,Y) = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)(y_i - \mu_y)$ n = number of samples x_i = parameter value for sample i μ_x = mean of x values y_i = parameter value for sample i μ_y = mean of y values
Confidence Interval $= \bar{x} \pm t\frac{s}{\sqrt{n}}$ where t = 1.96 for 0.05 alpha (95% confidence level) s = standard deviation of the sample n = number of samples	
Standard Deviation $= s = \sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}$ where n = number of samples x_i = parameter value for sample i	

Calculated Statistics – Detached Dwellings

Detached Housing								Framing Factors – NET				Ratios				
Code	City	Zone	House Type	Bsmnt	Stories	Surveyor	Floor Area	Ceiling F.F.	Wall F.F.	Floor F.F.	Overall F.F.	Corner Right to Wall Area	Exp Perim to Wall Area	Ceiling Opening to Ceiling	Floor Opening to Floor Area	Win+Dr Wall Ratios
D5	Redding	3	Single Detached	slab	1	Rick Chitwood	2517	7.2	27.5	0.0	14.1	0.4	0.0	0.0	0.0	22.8
D6	Redding	3	Single Detached	slab	1	Rick Chitwood	2433	7.5	30.0	0.0	11.6	0.4	0.0	0.2	0.0	18.5
D7	Chico	3	Single Detached	slab	1	Rick Chitwood	1995	8.6	25.9	0.0	12.6	0.4	0.0	0.4	0.0	17.1
D8	Chico	3	Single Detached	slab	1	Rick Chitwood	1659	6.5	23.2	0.0	10.1	0.4	0.0	0.3	0.0	16.3
D13	Redding	3	Single Detached	slab	1	Rick Chitwood	2418	10.6	26.1	0.0	14.4	0.6	0.0	0.0	0.0	23.4
D16	Sacramento	3	Single Detached	slab	1	Rick Chitwood	1872	7.1	24.4	0.0	11.8	0.6	0.0	0.3	0.0	15.7
D17	Sacramento	3	Single Detached	slab	1	Rick Chitwood	1973	6.7	24.2	0.0	11.9	0.6	0.0	0.0	0.0	17.9
D18	Sacramento	3	Single Detached	slab	1	Rick Chitwood	2251	6.5	29.2	0.0	12.7	0.6	0.0	0.2	0.0	17.5
D19	Sacramento	3	Single Detached	slab	2	Rick Chitwood	2873	5.7	30.3	0.0	13.1	0.6	0.0	0.0	0.0	15.7
D20	Rocklin	3	Single Detached	slab	1	Rick Chitwood	1684	5.4	32.5	0.0	16.5	0.4	0.0	0.0	0.0	21.8
D21	Rocklin	3	Single Detached	slab	2	Rick Chitwood	2519	7.5	30.1	0.0	16.9	0.4	6.4	0.6	0.0	21.7
D1	Brentwood	4	Single Detached	slab	2	Chitwood & Schumacher	2555	7.7	25.6	0.0	14.0	0.4	7.7	0.5	0.0	19.4
D2	Brentwood	4	Single Detached	slab	1	Chitwood & Schumacher	1981	7.5	28.0	0.0	11.3	0.6	0.0	0.3	0.0	19.8
D3	Doublin	4	Single Detached	slab	1	Chitwood & Schumacher	2357	6.7	26.4	0.0	11.0	0.4	0.0	0.4	0.0	19.1
D4	Doublin	4	Single Detached	slab	2	Chitwood & Schumacher	2984	6.6	27.7	0.0	13.7	0.6	1.7	0.6	0.0	19.9
D9	Davis	4	Single Detached	slab	2	Rick Chitwood	1315	7.0	25.7	0.0	18.3	0.8	7.4	0.6	0.0	13.5
D10	Davis	4	Single Detached	slab	2	Rick Chitwood	1467	6.6	25.7	0.0	14.8	0.6	6.1	0.5	0.0	13.4
D11	Vallejo	4	Single Detached	slab	2	Rick Chitwood	2326	7.0	23.9	0.0	11.7	0.4	2.5	0.4	0.0	13.8
D12	Vallejo	4	Single Detached	slab	2	Rick Chitwood	1983	5.4	22.7	0.0	11.9	0.4	2.1	0.0	0.0	13.9
D14	Vacaville	4	Single Detached	slab	2	Rick Chitwood	2043	6.2	26.1	0.0	12.3	0.5	4.6	0.5	0.0	14.5
D15	Vacaville	4	Single Detached	slab	2	Rick Chitwood	1536	7.0	24.9	0.0	15.5	0.6	4.0	0.0	0.0	13.4
D22	Bakersfield	4	Single Detached	slab	1	Rick Chitwood	1271	6.5	19.3	0.0	10.5	0.4	0.0	0.4	0.0	11.9
D23	Bakersfield	4	Single Detached	slab	1	Rick Chitwood	1489	7.1	22.3	0.0	10.2	0.5	0.0	0.3	0.0	14.7
D24	Bakersfield	4	Single Detached	slab	1	Rick Chitwood	1830	7.1	23.0	0.0	10.2	0.4	0.0	0.3	0.0	11.6
D25	Bakersfield	4	Single Detached	slab	1	Rick Chitwood	2068	6.9	24.4	0.0	10.3	0.4	0.0	0.2	0.0	14.5
D26	Bakersfield	4	Single Detached	slab	1	Rick Chitwood	1357	6.7	21.0	0.0	9.3	0.3	0.0	0.3	0.0	13.0
D27	Bakersfield	4	Single Detached	slab	1	Rick Chitwood	1859	5.6	21.1	0.0	10.8	0.4	5.3	0.0	0.0	11.5
D28	Simi Valley	4	Single Detached	slab	2	Rick Chitwood	2829	7.3	27.3	0.0	14.6	0.4	6.2	0.3	0.0	16.4
D29	Fairfield	4	Single Detached	slab	2	Rick Chitwood	2546	6.7	31.8	0.0	17.2	0.4	1.8	0.3	0.0	24.1
D30	Fairfield	4	Single Detached	slab	2	Rick Chitwood	2825	6.3	31.7	0.0	17.2	0.6	2.9	0.0	0.0	21.2
						Averages:	**Overall**	**6.9**	**26.1**	**0.0**	**13.0**	**0.5**	**4.5**	**0.4**	**0.0**	
							Zone 3	**7.2**	**27.6**	**0.0**	**13.3**	**0.5**	**6.4**	**0.3**	**0.0**	
							Zone 4	**6.7**	**25.2**	**0.0**	**12.9**	**0.5**	**4.4**	**0.4**	**0.0**	
						Standard Deviations:	**Overall**	**0.9**	**3.3**	**0.0**	**2.5**	**0.1**	**2.8**	**0.2**	**0.0**	
							Zone 3	**1.4**	**2.9**	**0.0**	**2.2**	**0.2**	**2.9**	**0.2**	**0.0**	
							Zone 4	**0.5**	**3.3**	**0.0**	**2.7**	**0.1**	**2.5**	**0.2**	**0.0**	
						Confidence	**5%**	**0.3**	**1.2**		**0.9**					
	Correlations to Net Wall Framing Factor:				**0.295225**		**0.61252809**					**0.09289257**	**0.04018628**	**-0.1084396**		**0.74974572**

Calculated Statistics – Attached Dwellings

Attached Housing								Framing Factors -- Net				Ratios				
Code	City	Zone	House Type	Bsmnt	Stories	Surveyor	Floor Area	Ceiling F.F.	Wall F.F.	Floor F.F.	Overall F.F.	Corner Hght to Wall Area	Exp Perim to Wall Area	Ceiling Opening to Ceiling Area	Floor Opening to Floor Area	
A8	Roseville	3	Single Attached	slab	1	Rick Chitwood	1642	6.9	22.2	0.0	11.0	0.6	0.0	0.4	0.0	20.9
A9	Roseville	3	Single Attached	slab	1	Rick Chitwood	1684	7.0	23.5	0.0	10.0	0.9	0.0	0.4	0.0	21.4
A1	Danville	4	Single Attached	slab	2	Chitwood & Schumacher	1792	8.7	30.6	0.0	14.9	0.8	3.0	0.5	0.0	20.2
A2	Thousand Oaks	4	Single Attached	slab	2	Rick Chitwood	2158	6.7	29.6	0.0	11.3	0.7	3.5	0.6	0.0	21.5
A3	Thousand Oaks	4	Single Attached	slab	2	Rick Chitwood	1757	7.6	31.4	0.0	13.7	0.8	2.8	0.0	0.0	26.8
A4	Thousand Oaks	4	Single Attached	slab	2	Rick Chitwood	1672	7.9	25.4	0.0	13.9	0.8	2.3	0.5	0.0	14.6
A5	Simi Valley	4	Single Attached	slab	2	Rick Chitwood	1678	6.5	24.0	0.0	10.1	0.7	4.1	0.0	0.0	13.8
A6	Simi Valley	4	Single Attached	slab	2	Rick Chitwood	1900	6.8	25.9	0.0	11.0	0.8	3.7	0.0	0.0	13.9
A7	Simi Valley	4	Single Attached	slab	2	Rick Chitwood	1344	6.6	23.7	0.0	12.7	0.7	1.0	0.0	0.0	13.9
A10	San Mateo	4	Single Attached	slab	2	Rick Chitwood	1216	9.3	25.1	0.0	17.9	0.6	2.6	0.8	0.0	15.1
A11	San Mateo	4	Single Attached	slab	2	Rick Chitwood	1594	6.6	27.7	0.0	17.9	1.3	1.9	0.6	0.0	20.5
A12	San Mateo	4	Single Attached	slab	2	Rick Chitwood	1259	7.7	25.7	0.0	15.4	1.6	5.4	0.7	0.0	16.5
A13	Chula Vista	4	Single Attached	slab	1	Rick Chitwood	1039	9.9	26.3	0.0	19.3	0.4	2.7	0.5	0.0	15.6
A14	Chula Vista	4	Single Attached	slab	2	Rick Chitwood	1131	7.0	27.6	0.0	14.3	0.9	2.5	0.8	0.0	21.1
A15	Chula Vista	4	Single Attached	slab	2	Rick Chitwood	1368	5.4	25.1	0.0	13.6	0.8	1.9	0.6	0.0	18.7
A16	Chula Vista	4	Single Attached	slab	2	Rick Chitwood	1471	5.9	31.7	0.0	12.1	0.9	2.7	0.6	0.0	26.0
A17	Chula Vista	4	Single Attached	slab	2	Rick Chitwood	1766	6.1	26.3	0.0	9.9	1.1	2.0	0.5	0.0	20.0
A18	Chula Vista	4	Single Attached	slab	2	Rick Chitwood	1141	9.4	28.0	0.0	23.0	0.8	4.6	0.6	0.0	19.4
						Averages:	**Overall**	**7.4**	**26.7**	**0.0**	**14.0**	**0.8**	**2.9**	**0.6**	**0.0**	
							Zone 3	**6.9**	**22.8**	**0.0**	**10.5**	**0.7**	**0.0**	**0.4**	**0.0**	
							Zone 4	**7.4**	**27.1**	**0.0**	**14.4**	**0.8**	**2.9**	**0.6**	**0.0**	
						Standard Deviations:	**Overall**	**1.1**	**2.4**	**0.0**	**3.5**	**0.3**	**1.3**	**0.3**	**0.0**	
							Zone 3	**0.7**	**1.3**	**0.0**	**1.7**	**0.1**	**0.5**	**0.4**	**0.0**	
							Zone 4	**1.2**	**2.1**	**0.0**	**3.6**	**0.3**	**1.3**	**0.3**	**0.0**	
						Confidence	**5%**	**0.5**	**1.1**		**1.6**					
	Correlations to Net Wall Framing Factor:				**0.443558**		**0.21194449**					**0.0924528**	**0.39251699**	**0.15801092**		**0.6503097**

Calculated Statistics – Multi-family Dwellings

Multi-Family Housing								Framing Factors -- Net				Ratios				
Code	City	Zone	House Type	Bsmnt	Stories	Surveyor	Floor Area/Unit	Ceiling F.F.	Wall F.F.	Floor F.F.	Overall F.F.	Corner Hght to Wall Area	Exp Perim to Wall Area	Ceiling Opening to Ceiling Area	Floor Opening to Floor Area	
M2	Roseville	3	Multi-Family	slab	2	Rick Chitwood	1119	4.2	25.4	0.0	18.6	0.7	11.1	0.4	0.0	17.0
M3	Roseville	3	Multi-Family	slab	3	Rick Chitwood	972	8.2	24.8	0.0	19.5	0.7	8.0	0.4	0.0	16.2
M7	Rocklin	3	Multi-Family	slab	3	Rick Chitwood	690	7.2	27.7	0.0	23.4	1.0	4.5	0.1	0.0	21.9
M8	Rocklin	3	Multi-Family	slab	2	Rick Chitwood	961	7.4	23.7	0.0	17.9	1.0	10.5	0.0	0.0	17.2
M1	Fairfield	4	Multi-Family	slab	2	Rick Chitwood	938	6.7	23.9	0.0	17.7	0.6	6.9	0.0	0.0	14.6
M4	Camerillo	4	Multi-Family	slab	2	Rick Chitwood	970	5.9	26.1	0.0	18.9	0.8	6.1	0.5	0.0	24.0
M5	Santa Clarita	4	Multi-Family	slab	2	Rick Chitwood	1156	8.1	28.6	0.0	19.6	0.9	2.6	0.6	0.0	28.2
M6	Valencia	4	Multi-Family	slab	3	Rick Chitwood	1140	6.8	29.9	0.0	25.3	1.2	7.2	0.0	0.0	23.2
M9	Valencia	4	Multi-Family	slab	3	Rick Chitwood	984	3.6	28.7	0.0	19.6	1.0	6.2	0.0	0.0	23.5
M10	Santa Clarita	4	Multi-Family	slab	3	Rick Chitwood	956	6.9	28.6	0.0	25.3	0.9	7.6	0.5	0.0	20.5
M11	Chula Vista	4	Multi-Family	slab	3	Rick Chitwood	1052	12.7	26.5	0.0	23.5	0.9	9.1	0.0	0.0	16.8
M12	Valencia	4	Multi-Family	slab	3	Rick Chitwood	798	2.4	32.4	0.0	25.4	1.1	5.7	0.0	0.0	27.4
						Averages:	**Overall**	**6.7**	**27.2**	**0.0**	**21.2**	**0.9**	**7.1**	**0.4**	**0.0**	
							Zone 3	**6.7**	**25.4**	**0.0**	**19.8**	**0.9**	**8.5**	**0.3**	**0.0**	
							Zone 4	**6.6**	**28.1**	**0.0**	**21.9**	**0.9**	**6.4**	**0.5**	**0.0**	
						Standard Deviations:	**Overall**	**2.5**	**2.5**	**0.0**	**2.9**	**0.2**	**2.8**	**0.3**	**0.0**	
							Zone 3	**0.9**	**2.3**	**0.0**	**0.9**	**0.2**	**3.3**	**0.3**	**0.0**	
							Zone 4	**3.0**	**2.2**	**0.0**	**2.4**	**0.1**	**1.2**	**0.2**	**0.0**	
						Confidence	**5%**	**1.4**	**1.4**		**1.6**					
	Correlations to Net Wall Framing Factor:				**0.55951**		**0.1288701**					**0.73192054**	**-0.5191889**	**-0.0882753**		**0.81255875**

ASTM E283 RESULTS

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BAMCORE, LLC
TEST REPORT

SCOPE OF WORK
ASTM E283 TESTING ON HIGH FRAMING FACTOR, WALL ASSEMBLY #2

REPORT NUMBER
I5420.01-109-44

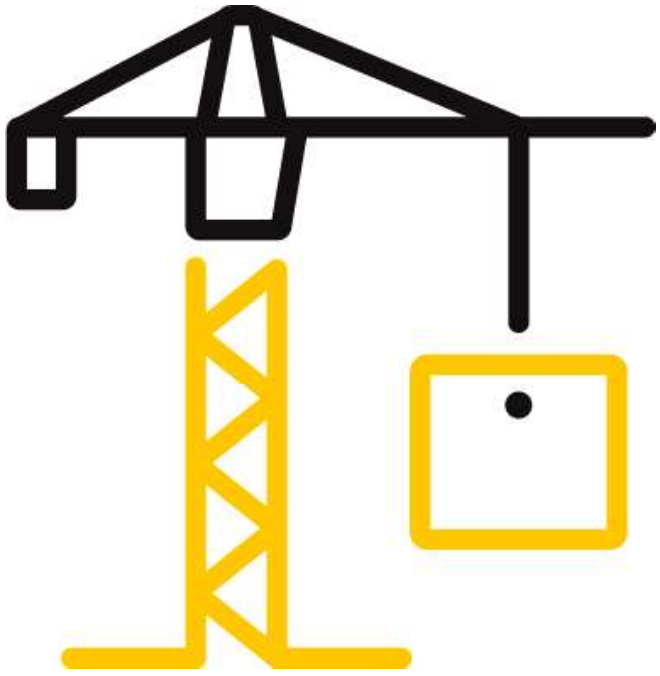
TEST DATE(S)
06/19/18

ISSUE DATE **REVISED DATE**
07/09/18 07/09/18

RECORD RETENTION END DATE
06/19/22

PAGES
11

DOCUMENT CONTROL NUMBER
ATI 00479 (07/24/17)
RT-R-AMER-Test-2805



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TEST REPORT FOR BAMCORE, LLC
Report No.: I5420.01-109-44
Revision 1: 07/09/18
Date: 07/09/18

REPORT ISSUED TO

BAMCORE, LLC
5900 Pruitt Avenue #110
Windsor, California 95492

SECTION 1

SCOPE

Intertek Building & Construction (B&C) was contracted by BamCore, LLC to perform testing in accordance with ASTM E283 on their High Framing Factor, #2 wall assembly. Results obtained are tested values and were secured by using the designated test method(s). Testing was conducted at Intertek B&C test facility in York, Pennsylvania.

This report does not constitute certification of this product nor an opinion or endorsement by this laboratory.

SECTION 2

SUMMARY OF TEST RESULTS

TITLE	RESULTS
Air Infiltration at 6.27 psf	<0.1 L/s/m^2 (<0.01 cfm/ft^2)
Air Exfiltration at 6.27 psf	<0.1 L/s/m^2 (<0.01 cfm/ft^2)

For INTERTEK B&C:

COMPLETED BY:	Ken R. Stough	**REVIEWED BY:**	Timothy J. McGill
TITLE:	Lead Technician – Product Testing	**TITLE:**	Manager – Product Testing
SIGNATURE:	Digitally Signed by: Ken R. Stough	**SIGNATURE:**	Digitally Signed by: Timothy J. McGill
DATE:	07/09/18	**DATE:**	07/09/18

KRS:wnl

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SECTION 3
TEST METHOD(S)

The specimen was evaluated in accordance with the following:

> **ASTM E283-04(2012)**, *Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen*

SECTION 4
MATERIAL SOURCE/INSTALLATION

Test specimen was provided by the client. Representative samples of the test specimen(s) will be retained by Intertek B&C for a minimum of two years from the test completion date.

The specimen was installed into a Spruce-Pine-Fir wood buck. The rough opening allowed for no shim spacing. The interior and exterior perimeter of the wall was sealed with sealant. Installation of the tested product was performed by the Intertek B&C.

LOCATION	ANCHOR DESCRIPTION	ANCHOR LOCATION
Top, bottom plates, and sides	#8 x 3" drywall screws	Located 6" from each corner and spaced 8" on center through the wood buck into the test wall

SECTION 5
EQUIPMENT

Control Panel: 003921
Weather Station: 63316

SECTION 6
LIST OF OFFICIAL OBSERVERS

NAME	COMPANY
Timothy J. McGill	Intertek B&C
Ken R. Stough	Intertek B&C

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TEST REPORT FOR BAMCORE, LLC
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SECTION 7
TEST SPECIMEN DESCRIPTION

Product Type: Wall Assembly #2
Series/Model: High Framing Factor

Product Size(s):

OVERALL AREA:	**WIDTH**		**HEIGHT**	
5.9 m² (64.0 ft²)	**millimeters**	**inches**	**millimeters**	**inches**
Overall Size	2438	96	2438	96

Test Specimen Description*:
The BamCore Prime Panel wall system was comprised of two laminated veneer bamboo (LVB) panels forming the interior and exterior faces of the wall assembly. The panels were fastened to wood plates. The framing factor of 6.65% was chosen to match a wall with a surface area that consisted of 12% window area and 7% door area. The wall was drawn to show how much panel-to-panel framing would be required for window, door, and transverse stiffness blocking and single top and bottom plates. The percent window and door areas came from the document, “Characterization of Framing Factors for Low-Rise Residential Building Envelopes in California,” which was prepared for the California Energy Commission by Enermodal Engineering Limited, in association with Chitwood Energy Management, dated November 2001. The test specimen was 96" by 96" by 8-5/8". The specimen consisted of 5/8" Type "X" drywall, Proprietary BamCore Prime Panel, nominal 6x width of cellulose insulation, and Proprietary BamCore Prime Panel. The corner drywall screws were 3/4" by 3/4" in from the corners of the drywall. The screw spacing was based off the corner screw location. The drywall screw spacing was 15-3/4" horizontally and 11-5/8" vertically throughout the field and perimeter.

TOTAL WEIGHT (lbs)	**AVERAGE WEIGHT** (lbs/ft²)
878	13.72

** - Stated per Client/Manufacturer*

Drawings of the test specimen are included in Section 12.

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TEST REPORT FOR BAMCORE, LLC
Report No.: I5420.01-109-44
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Date: 07/09/18

SECTION 8
TEST RESULTS

The temperature during testing was 27°C (81°F). The results are tabulated as follows:

Air Infiltration

Pressure (psf)	Total (cfm)	Tare (cfm)	Net (cfm)	Rate (cfm/ft^2)	Notes
1.57	0.85	0.83	0.02	0.0003	1, 2
6.27	2.55	2.51	0.04	0.0006	1, 2

Air Exfiltration

Pressure (psf)	Total (cfm)	Tare (cfm)	Net (cfm)	Rate (cfm/ft^2)	Notes
1.57	0.80	0.79	0.01	0.0002	1, 2
6.27	2.41	2.40	0.01	0.0002	1, 2

***General Note**: All testing was performed in accordance with the referenced standard(s).*

Note 1: The control panel was calibrated to only two decimal places (0.00). Stated values are calculated using cfm/sq.ft.

Note 2: Test Date 06/19/18 / Time: 11:36 AM

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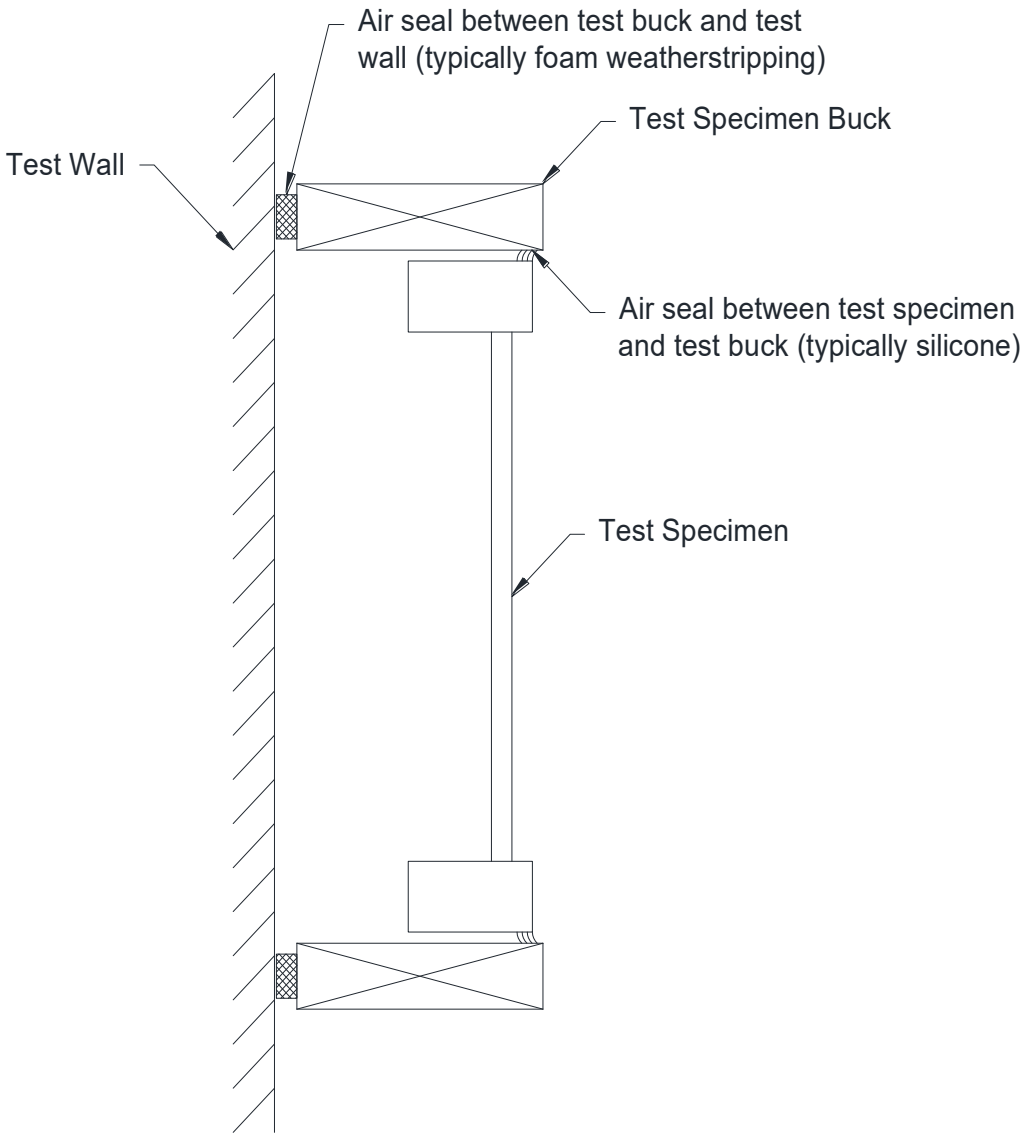
SECTION 9
LOCATION OF AIR SEAL

The air seal between the test specimen and the test wall is detailed below. The seal is made of foam weatherstripping and is attached to the edge of the test specimen buck. The test specimen buck is placed against the test wall and clamped in place, compressing the weatherstripping and creating a seal.



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TEST REPORT FOR BAMCORE, LLC
Report No.: I5420.01-109-44
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SECTION 10
PHOTOGRAPH

Photo No. 1
High Framing Factor Wall Assembly #2

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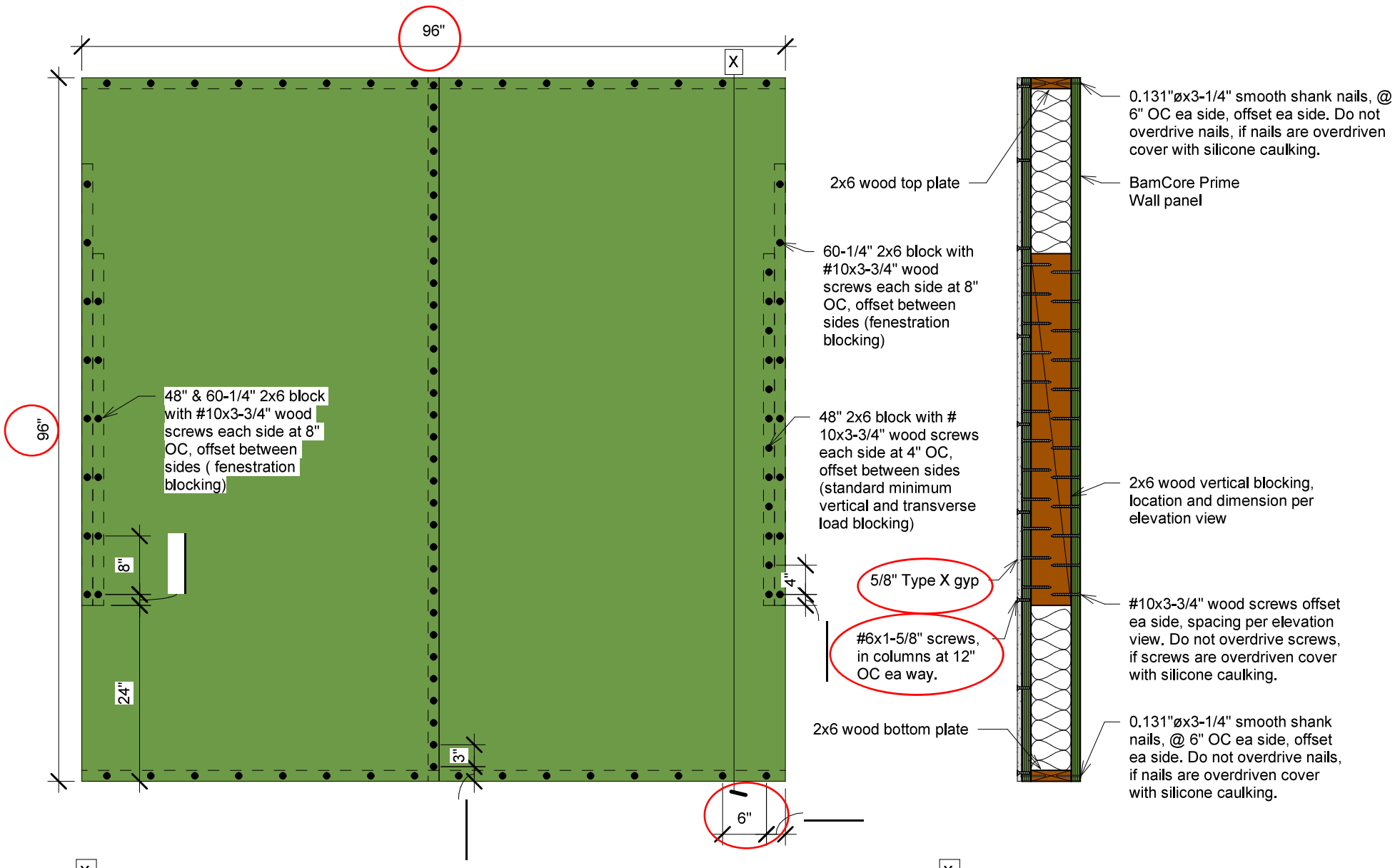
SECTION 11
DRAWINGS

The test specimen drawings have been reviewed by Intertek B&C and are representative of the test specimen(s) reported herein. Test specimen construction was verified by Intertek B&C per the drawings included in this report. Any deviations are documented herein or on the drawings.



6.65% Framing Factor BamCore Prime Wall

BamCore Section

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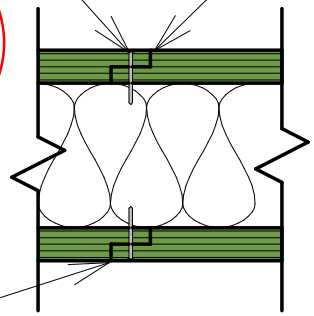
Report #:	I5420.01-109-44
Date:	07/09/2018
Verified by:	

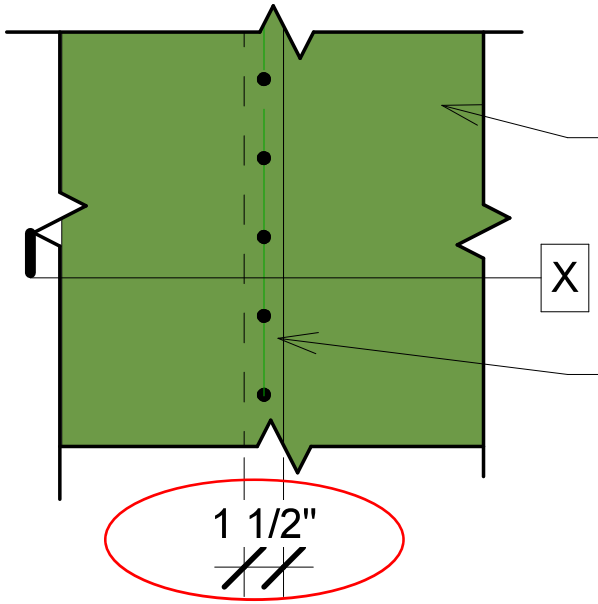
0.113"øx2" ring shank nails, @ 3" OC ea side offset. Do not overdrive nails, if nails are overdriven cover with silicone caulking.



Fill outer exposed joint with silicone caulking after nailing each side of wall.

Halflap joint

X BamCore Half Lap Plan Section



BamCore Prime Wall Panel

Halflap joint

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Report #: I5420.01-109-44
Date: 07/09/2018
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- Partial BamCore Half Lap Elevation

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City, State ZIP

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TEST REPORT FOR BAMCORE, LLC
Report No.: I5420.01-109-44
Revision 1: 07/09/18
Date: 07/09/18

SECTION 12
REVISION LOG

REVISION #	DATE	PAGES	REVISION
0	07/09/18	N/A	Original Report Issue
1	07/09/18	1	The pages total was incorrectly written as "111" instead of "11".

ASTM 1363 RESULTS

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BAMCORE, LLC
THERMAL PERFORMANCE TEST REPORT

SCOPE OF WORK
BAMCORE HIGH FRAMING FACTOR (6.65% FRAMING FACTOR BAMCORE PRIME WALL)

REPORT NUMBER
I4810.03-116-46 R0

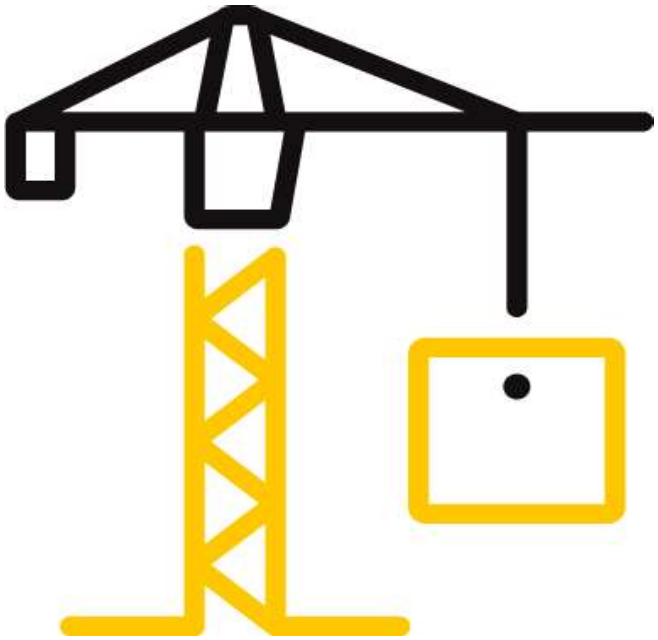
TEST DATE
06/19/18

ISSUE DATE
07/09/18

RECORD RETENTION END DATE
06/19/23

PAGES
21

DOCUMENT CONTROL NUMBER
ATI 00023(a) (07/24/17)
RTTDS-R-AMER-Test-2818(a)



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TEST REPORT FOR BAMCORE, LLC
Report No.: I4810.03-116-46 R0
Date: 07/09/18

REPORT ISSUED TO

BAMCORE, LLC
5900 Pruitt Avenue #110
Windsor, California 95492

SECTION 1

SCOPE

SERIES/MODEL: BAMCORE High Framing Factor (6.65% Framing Factor BamCore Prime Wall)

TYPE: Insulated Wall System

Intertek Building & Construction (Intertek B&C) was contracted by BAMCORE, LLC to evaluate the thermal performance per ASTM C1363-2011. The purpose of this testing was to evaluate the U-Factor performance. Results obtained are tested values and were secured by using the designated test method. Testing was conducted at Intertek B&C test facility in York, Pennsylvania. This report does not constitute certification of this product nor an opinion or endorsement by this laboratory.

SECTION 2

SUMMARY OF TEST RESULTS

Thermal Transmittance (U):	0.047 Btu/hr·ft^2·F
Specimen Thermal Resistance (R):	20.33 hr·ft^2·F/Btu

For INTERTEK B&C:

COMPLETED BY	Shon W. Einsig	**REVIEWED BY**	Ryan P. Moser
TITLE	Technician Team Leader, IIRC	**TITLE**	Senior Technician
SIGNATURE	Shon W. Einsig Digitally Signed by: Shon W. Einsig	**SIGNATURE**	Ryan P. Moser Digitally Signed by: Ryan P. Moser
DATE	07/09/18	**DATE**	07/09/18

SWE:kmm

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TEST REPORT FOR BAMCORE, LLC
Report No.: I4810.03-116-46 R0
Date: 07/09/18

SECTION 3
TEST SPECIMEN SUMMARY

SERIES/MODEL	BAMCORE High Framing Factor (6.65% Framing Factor BamCore Prime Wall)
TYPE	Insulated Wall System
OVERALL SIZE	96" x 96"
TEST SAMPLE SUBMITTED BY	Client

SECTION 4
TEST METHOD

The specimens were evaluated in accordance with the following:

> **ASTM C1363-2011**, Standard Test Method for the Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus

SECTION 5
MATERIAL SOURCE/INSTALLATION

Test samples were provided by BAMCORE, LLC. Representative samples of the test specimen will be retained by Intertek B&C for a minimum of five years from the test completion date.

Test Chamber Installation

The test sample was installed in a vertical orientation, the exterior of the specimen was exposed to the cold side.

SECTION 6
LIST OF OFFICIAL OBSERVERS

NAME	COMPANY
Joel T. Chronister	Intertek B&C
Shon W. Einsig	Intertek B&C
Ryan P. Moser	Intertek B&C

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TEST REPORT FOR BAMCORE, LLC
Report No.: I4810.03-116-46 R0
Date: 07/09/18

SECTION 7
TEST SAMPLE DESCRIPTION

CONSTRUCTION	The test wall was constructed as listed below, from the interior towards the exterior surface. *(see attached drawings)*
OVERALL SIZE	96" x 96"

Interior - (2) 4'x8' sheets of 5/8" Type "X" gypsum, horizontally installed with #6 x 1-5/8" screws, at 16" OC horizontally, and at 12" OC vertically. The exposed gypsum seam was filled with silicone caulking.

(2) 4'x8' sheets of 1-1/4" BamCore Prime Wall panels, vertically installed with 0.131"Øx3-1/4" smooth shank nails, at 6" OC and offset from the exterior BamCore Prime Wall panels. The half lap center vertical seam was nailed with 0.013"Øx2" ring shank nails, at 3" OC, and the exposed joint was filled with silicone caulking.

The base wall was constructed of 2x6 wood top and bottom plates. There were 2 additional 60-1/4" 2x6 blocking, and 2 additional 48" 2x6 wood blocking at each jamb, installed with #10x3-3/4" wood screws, offset *(see drawings)* .

The cavitity was filled with 3.5 density*, dry cellulose blown-in insulation.

(2) 4'x8' sheets of 1-1/4" BamCore Prime Wall panels, vertically installed with 0.131"Øx3-1/4" smooth shank nails, at 6" OC and offset from the interior BamCore Prime Wall panels. The half lap center vertical seam was nailed with 0.013"Øx2" ring shank nails, at 3" OC, and the exposed joint was filled with silicone caulking.

**Stated per Client/Manufacturer*

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TEST REPORT FOR BAMCORE, LLC
Report No.: I4810.03-116-46 R0
Date: 07/09/18

SECTION 8
THERMAL TRANSMITTANCE (U-FACTOR): MEASURED TEST DATA

Heat Flows

1.	Total Measured Input into Metering Box (Qtotal)	199.15	Btu/hr
2.	Surround Panel Heat Flow (Qsp)	9.14	Btu/hr
3.	Surround Panel Thickness	12.00	inches
4.	Surround Panel Conductance	0.0166	Btu/hr·ft^2·F
5.	Metering Box Wall Heat Flow (Qmb)	1.11	Btu/hr
6.	EMF vs Heat Flow Equation (equivalent information)	-2,087.6681*EMF + -0.224	
7.	Flanking Loss Heat Flow (Qfl)	39.59	Btu/hr
8.	Net Specimen Heat Loss (Qs)	149.32	Btu/hr

Areas

1.	Test Specimen Projected Area (As)	64.00	ft^2
2.	Metering Box Opening Area (Amb)	75.11	ft^2
3.	Metering Box Baffle Area (Ab1)	70.84	ft^2
4.	Surround Panel Interior Exposed Area (Asp)	11.11	ft^2

Test Conditions

1.	Average Metering Room Air Temperature (th)	100.00	F
2.	Average Cold Side Air Temperature (tc)	49.99	F
3.	Average Guard/Environmental Air Temperature	100.00	F
4.	Metering Room Average Relative Humidity	47.99	%
5.	Metering Room Maximum Relative Humidity	48.15	%
6.	Metering Room Minimum Relative Humidity	47.80	%
7.	Measured Cold Side Wind Velocity (Perpendicular Flow)	11.66	mph
8.	Measured Warm Side Wind Velocity (Parallel Flow)	N/A	mph
9.	Measured Static Pressure Difference Across Test Specimen	0.00" ± 0.04"	H_2O

Average Surface Temperatures

1.	Metering Room Surround Panel	98.42	F
2.	Cold Side Surround Panel	49.00	F

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TEST REPORT FOR BAMCORE, LLC
Report No.: I4810.03-116-46 R0
Date: 07/09/18

SECTION 9
THERMAL TRANSMITTANCE (U-FACTOR): CALCULATED TEST DATA

Results

1.	Thermal Conductance	0.05	Btu/hr·ft^2·F
2.	Thermal Resistance	20.33	hr·ft^2·F/Btu
3.	Overall Thermal Resistance (Ru)	21.44	hr·ft^2·F/Btu
4.	Warm Side Surface Resistance (Rh)	1.32	hr·ft^2·F/Btu
5.	Cold Side Surface Resistance (Rc)	-0.21	hr·ft^2·F/Btu
6.	Warm Side Surface Conductance (hh)	0.76	Btu/hr·ft^2·F
7.	Cold Side Surface Conductance (hc)	-4.67	Btu/hr·ft^2·F
8.	Thermal Transmittance of Test Specimen (U)	0.05	Btu/hr·ft^2·F

SECTION 10
TEST DURATION

1. The environmental systems were started at 06/16/2018 10:41.
2. The test parameters were considered stable for two consecutive four hour test periods from 06/18/2018 21:57 to 06/19/2018 05:57.
3. The thermal performance test results were derived from 06/19/2018 01:57 to 06/19/2018 05:57.

ANSI/NCSL Z540-2-1997 type B uncertainty for this test was 3.21%.

The sample was inspected for the formation of frost or condensation, which may influence the surface temperature measurements. The sample showed no evidence of condensation/frost at the conclusion of the test.

The direction of heat transfer was from the interior (warm side) to the exterior (cold side) of the specimen. The ratings were rounded in accordance to NFRC 601, NFRC Unit and Measurement Policy. The data acquisition frequency is 5 minutes.

Required annual calibrations for the Intertek B&C, 'thermal test chamber' (ICN 000001) in York, Pennsylvania were last conducted in July 2017 in accordance with Intertek B&C calibration procedure. A CTS Calibration verification was performed July 2017. A Metering Box Wall Transducer and Surround Panel Flanking Loss Characterization was performed July 2017.

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TEST REPORT FOR BAMCORE, LLC
Report No.: I4810.03-116-46 R0
Date: 07/09/18

SECTION 11
SURFACE TEMPERATURES

	WARM SIDE (F)	COLD SIDE (F)
1	97.61	48.88
2	97.68	49.31
3	97.51	49.36
4	97.73	49.28
5	97.37	49.33
6	97.01	49.40
7	97.58	49.00
8	97.98	49.41
9	97.90	59.24
10	97.70	49.23
11	97.62	49.29
12	97.44	NA
13	97.93	48.82
14	98.02	48.71
15	98.39	48.86
16	NA	49.03
17	97.85	48.58
18	97.80	48.39
19	94.71	49.78
20	94.49	49.41
21	97.64	49.19
22	94.63	49.15
23	94.56	49.08
24	98.22	48.78
25	95.53	49.06
26	92.30	48.60
AVERAGE	96.93	49.49

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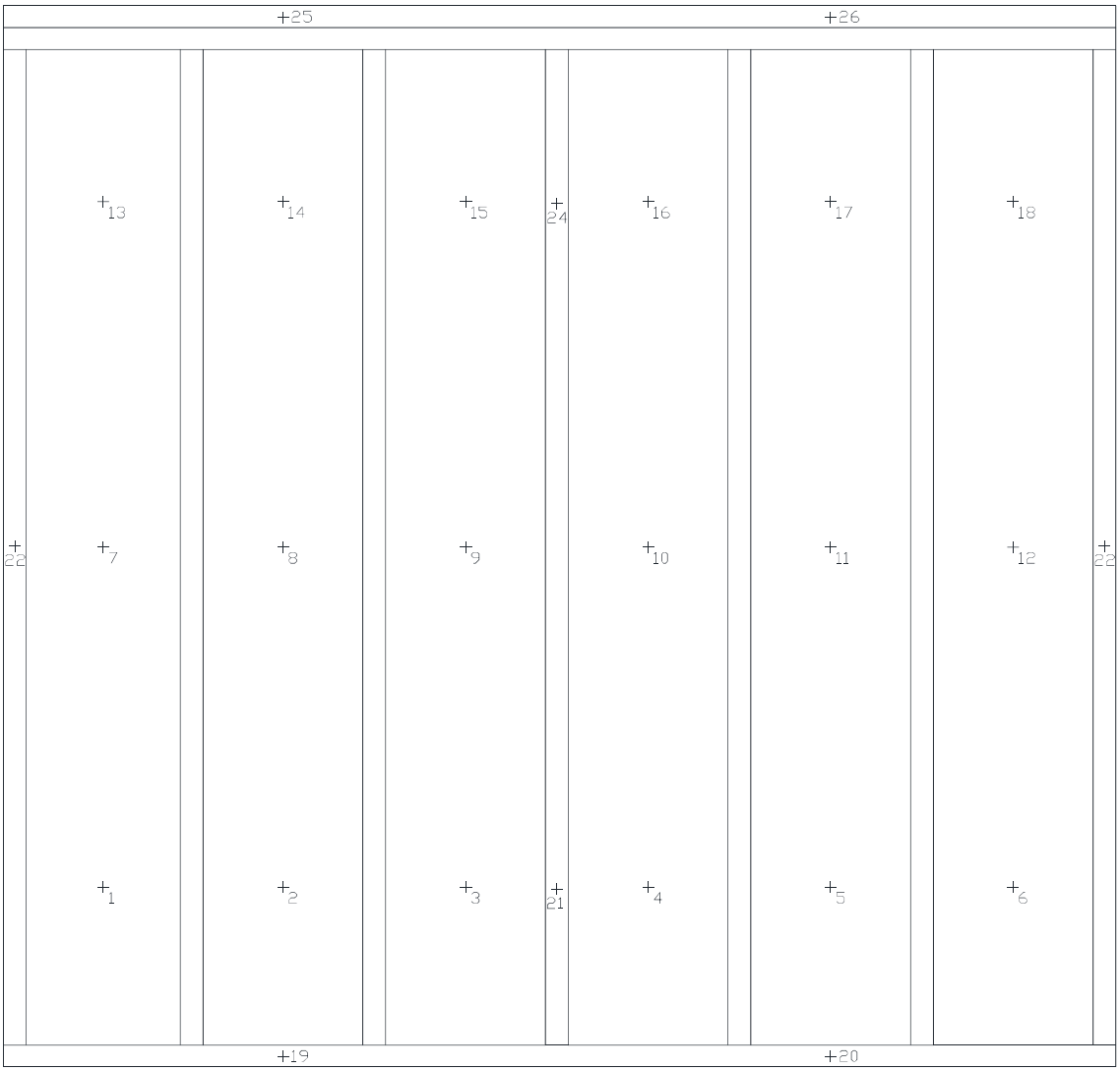
TEST REPORT FOR BAMCORE, LLC
Report No.: I4810.03-116-46 R0
Date: 07/09/18

SECTION 11 CONT.

THERMOCOUPLE LOCATION DIAGRAM



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SECTION 12
PHOTOGRAPHS

Photo #1, Exterior of wall assembly installed

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SECTION 12 CONT.

PHOTOGRAPHS

Photo #2, Interior of wall assembly installed

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SECTION 12 CONT.

PHOTOGRAPHS

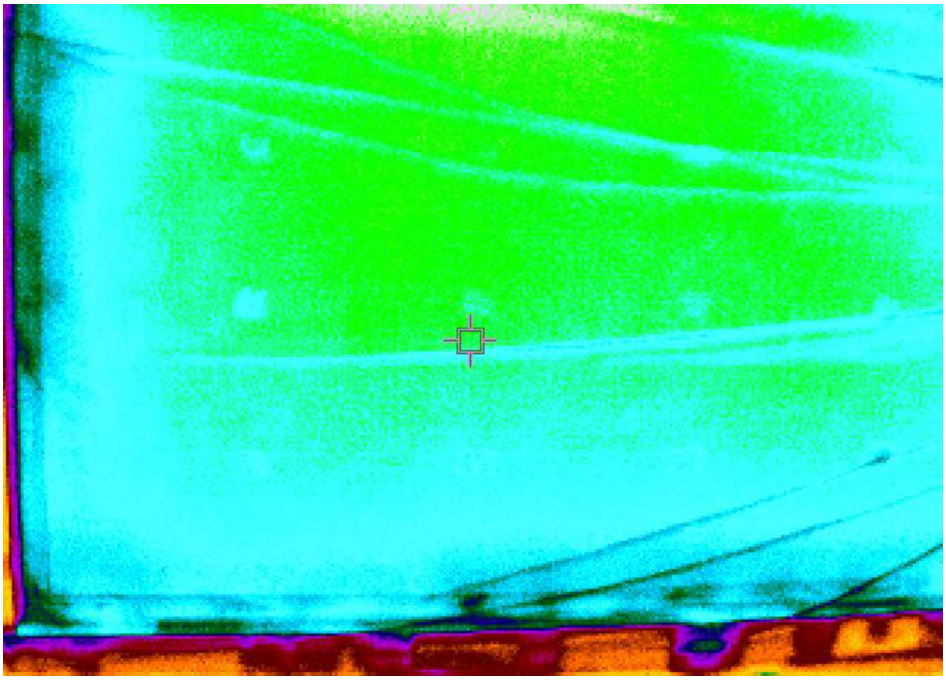

Photo #3, Interior of wall assembly installed (bottom left corner)

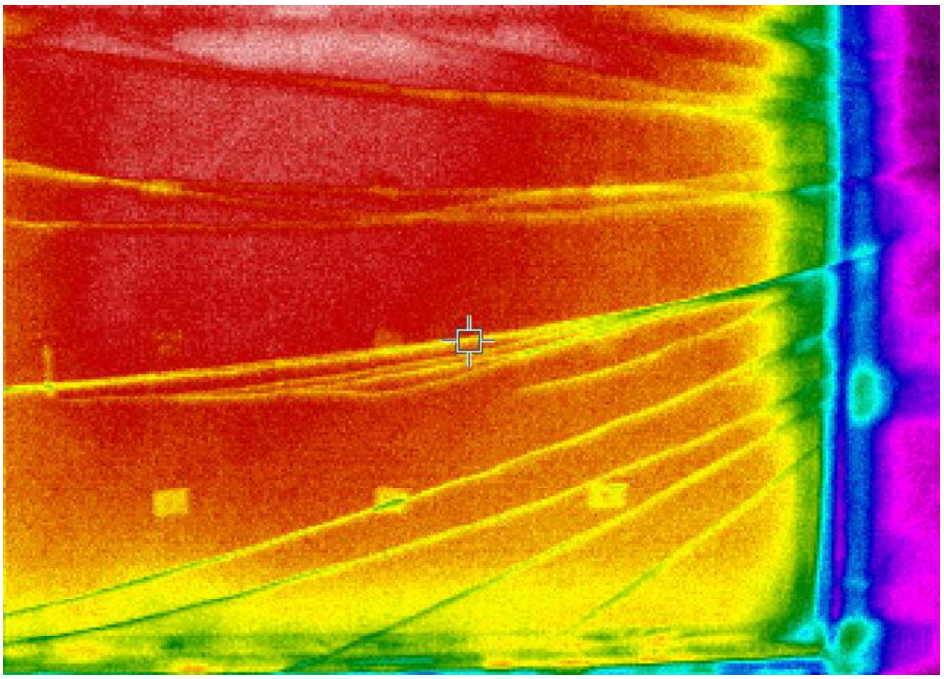

Photo #4, Interior of wall assembly installed (bottom right corner)

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SECTION 12 CONT.

PHOTOGRAPHS

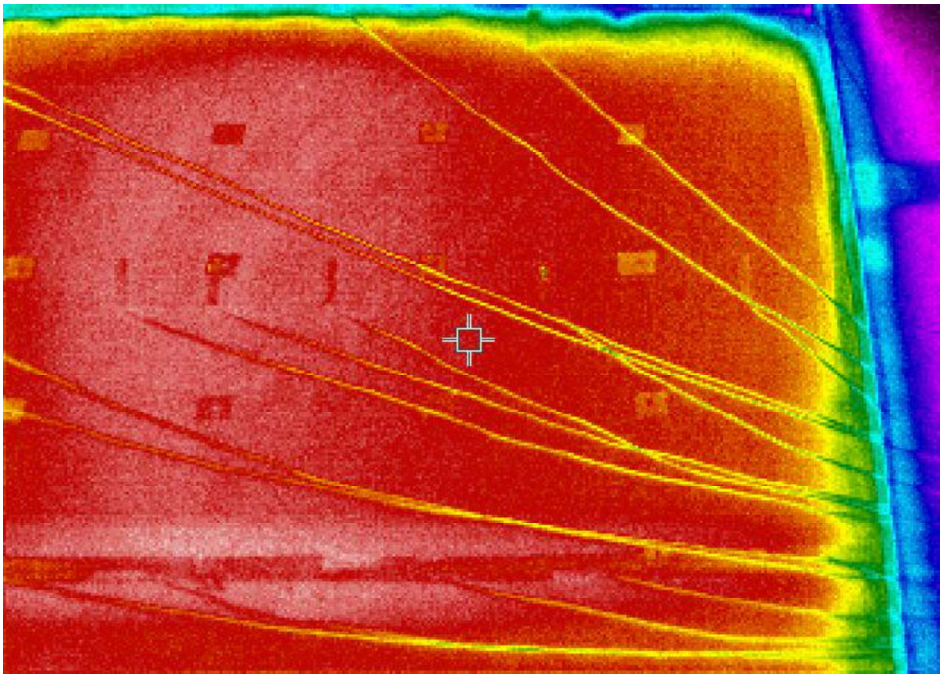

Photo #5, Interior of wall assembly installed (top right corner)

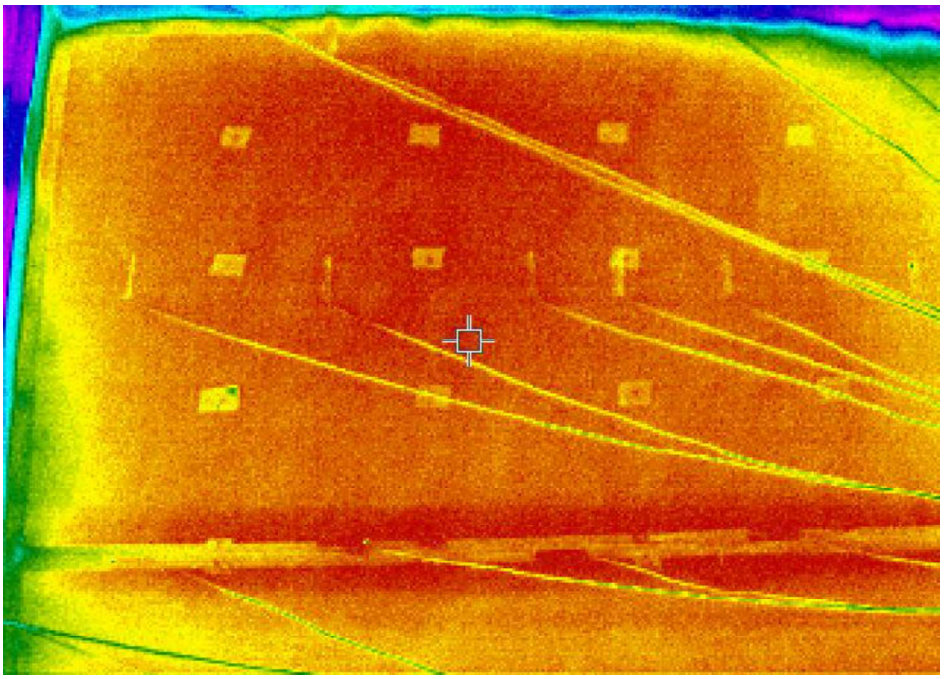

Photo #6, Interior of wall assembly installed (top left corner)

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SECTION 12 CONT.

PHOTOGRAPHS

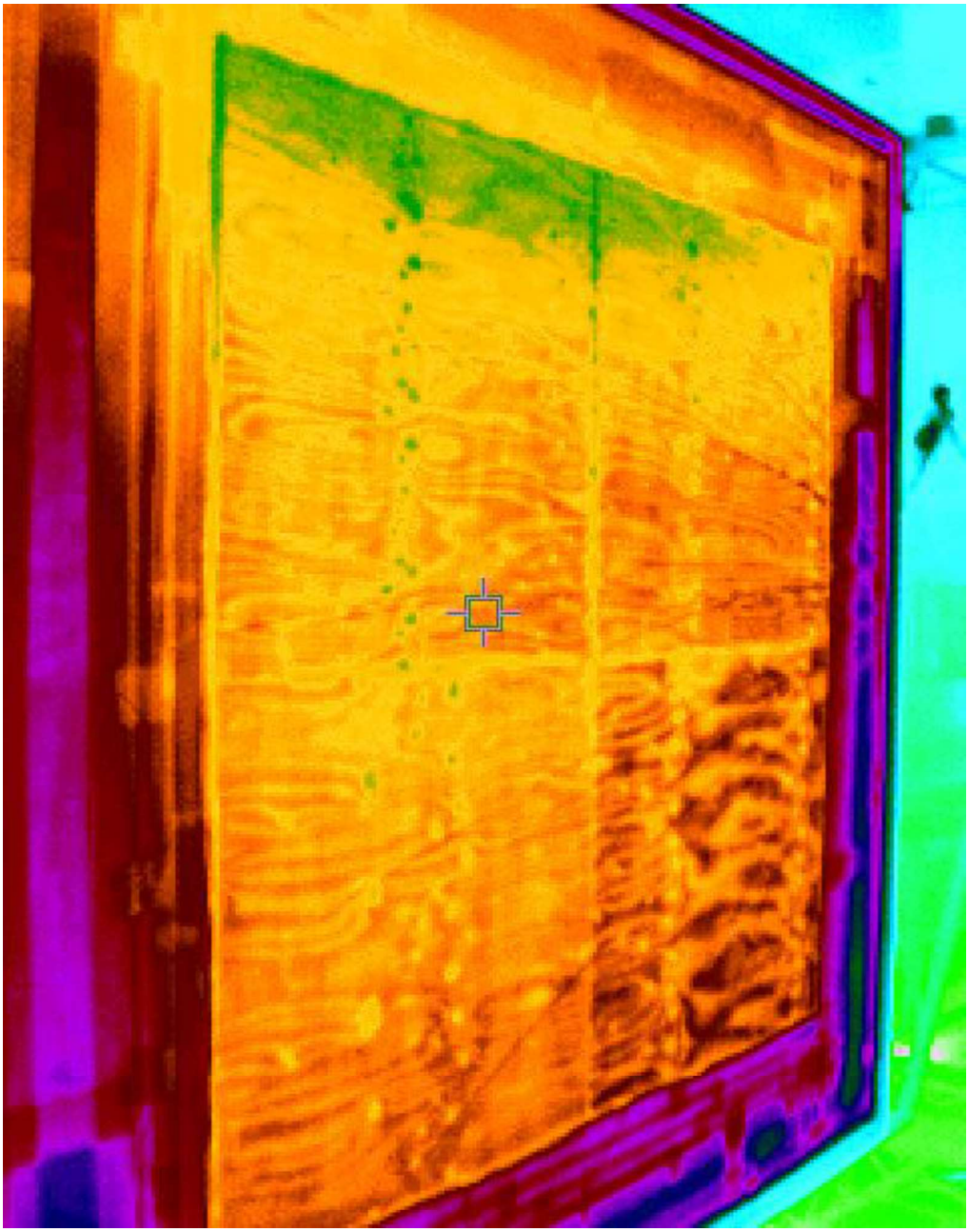

Photo #7, Interior of wall assembly installed

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York, Pennsylvania 17406

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SECTION 12 CONT.

PHOTOGRAPHS

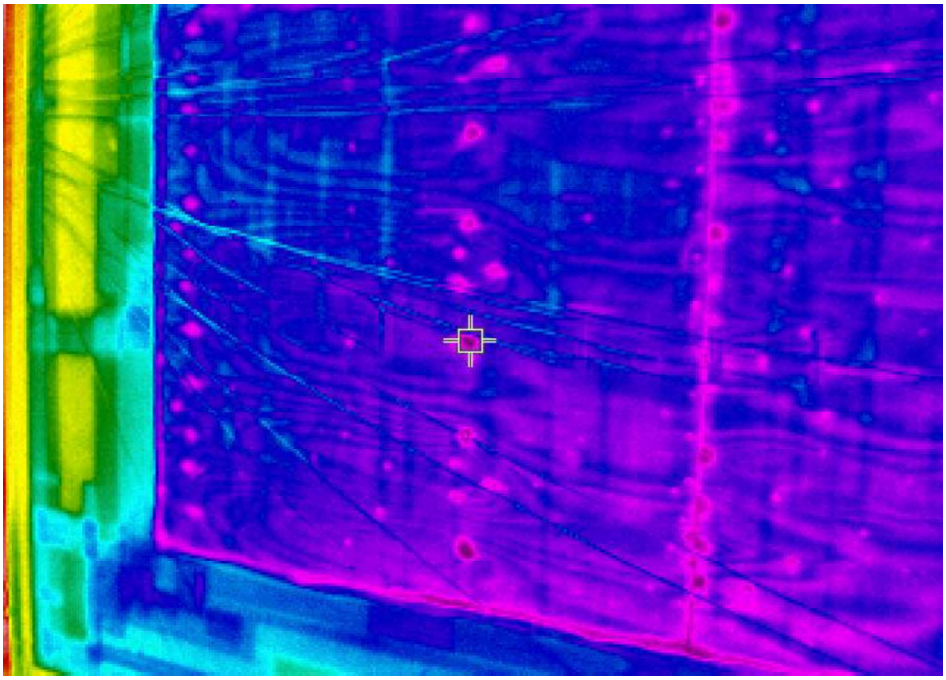

Photo #8, Exterior of wall assembly installed (bottom left corner)

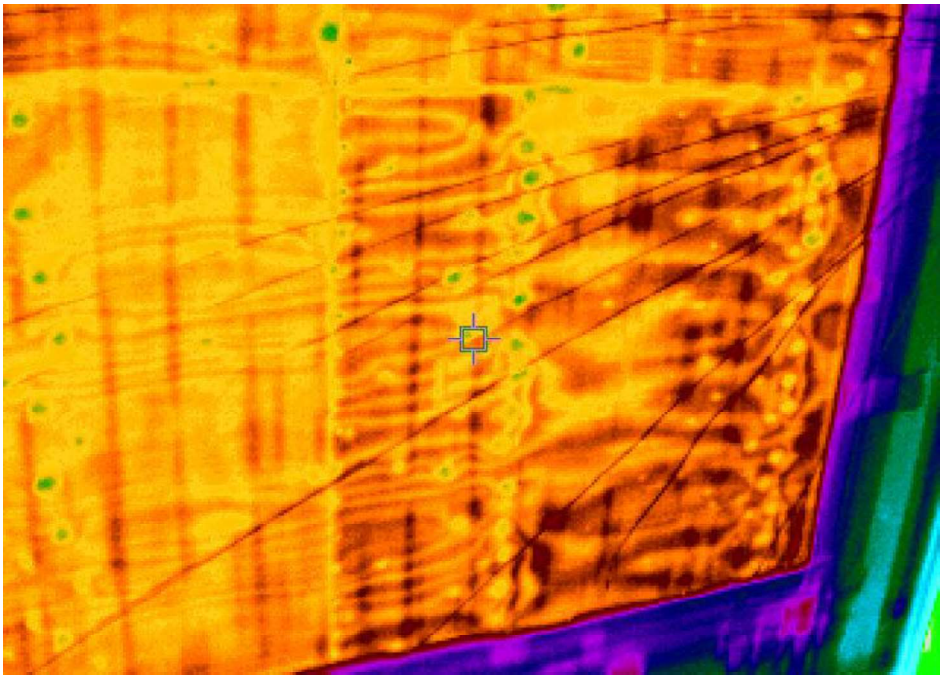

Photo #9, Exterior of wall assembly installed (bottom right corner)

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SECTION 12 CONT.

PHOTOGRAPHS

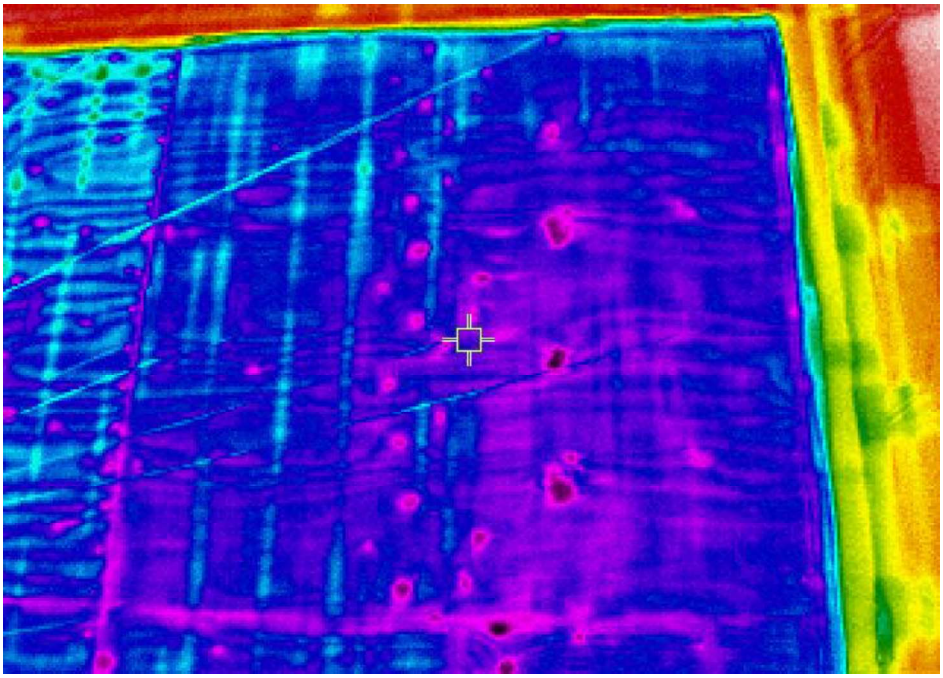

Photo #10, Exterior of wall assembly installed (top right corner)

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SECTION 12 CONT.

PHOTOGRAPHS

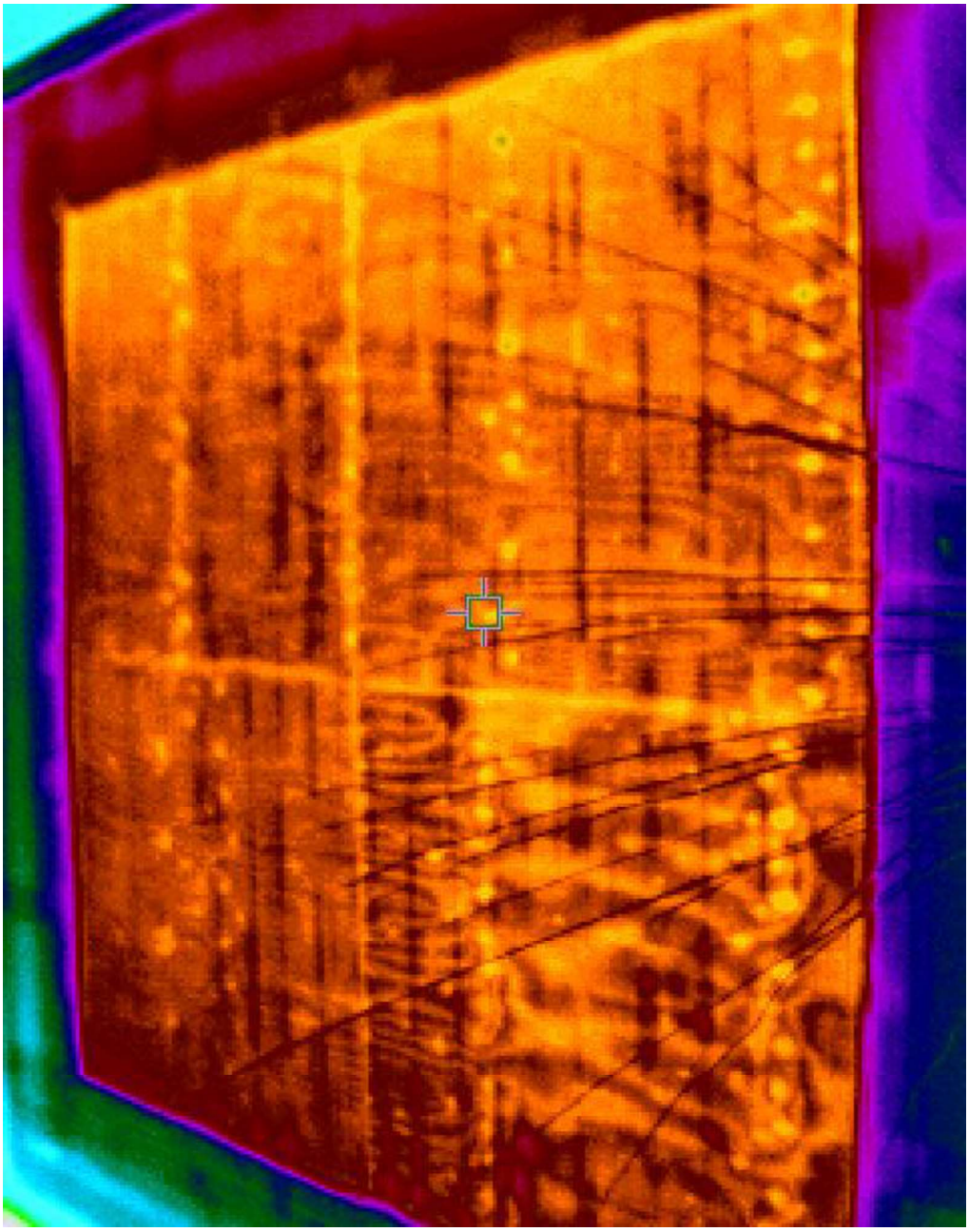

Photo #11, Exterior of wall assembly installed

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York, Pennsylvania 17406

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Facsimile: 717-764-4129
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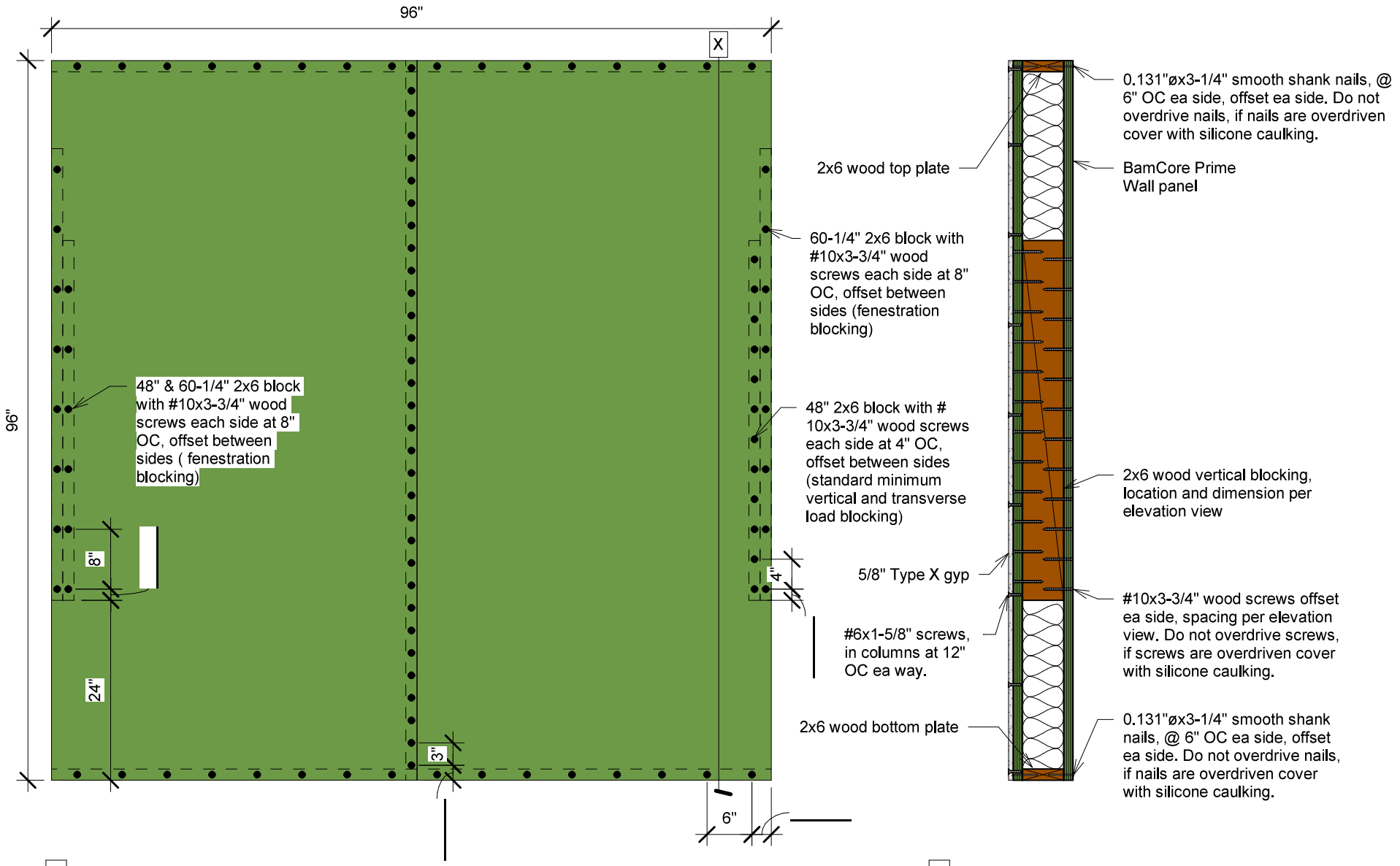
SECTION 13
DRAWINGS

The test specimen drawings which follow have been reviewed by Intertek B&C and are representative of the test specimen(s) reported herein. Test specimen construction was verified by Intertek B&C per the drawings included in this report. Any deviations are documented herein or on the drawings.



6.65% Framing Factor BamCore Prime Wall

BamCore Section

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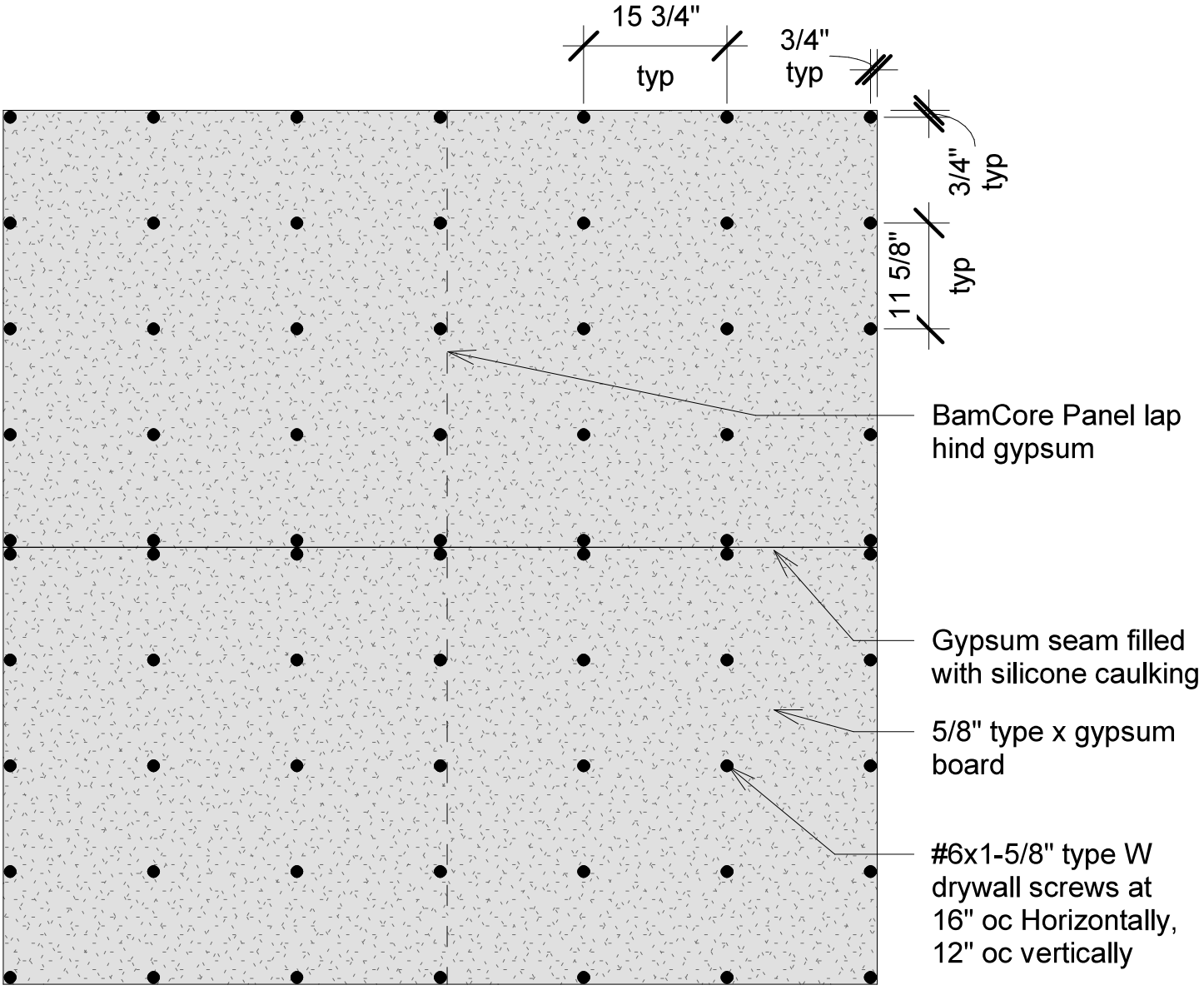
Report #: I4810.03-116-46
Date: 07/02/2018
Verified by:



X

Single Layer Gypsum Layout on BamCore Walls

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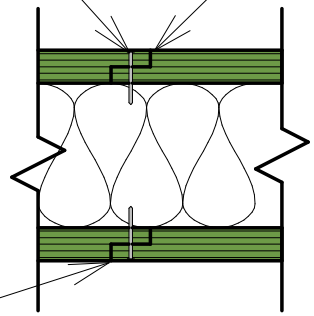
Report #:	I4810.03-116-46
Date:	07/02/2018
Verified by:	

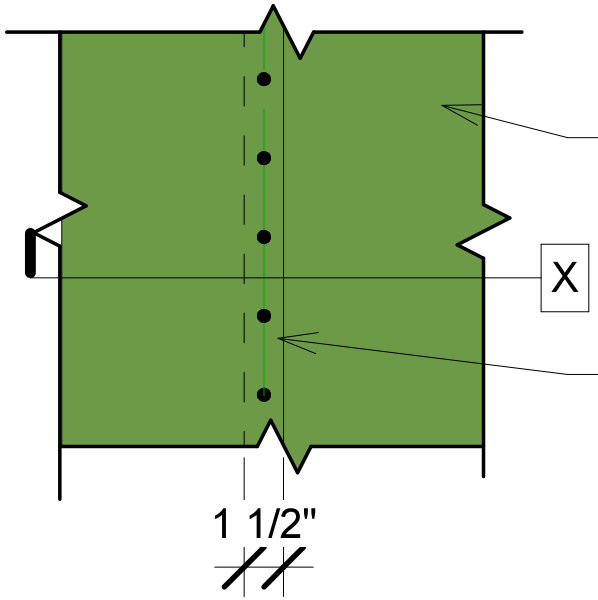
0.113"øx2" ring shank nails, @ 3" OC ea side offset. Do not overdrive nails, if nails are overdriven cover with silicone caulking.



Fill outer exposed joint with silicone caulking after nailing each side of wall.

Halflap joint

X BamCore Half Lap Plan Section



- Partial BamCore Half Lap Elevation

intertek Total Quality. Assured.

Report #: I4810.03-116-46
Date: 07/02/2018
Verified by:

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SECTION 14
REVISION LOG

REVISION #	DATE	PAGES	REVISION
.03 R0	07/09/18	N/A	Original Report Issue

ASTM C518-17

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York, PA 17406

Telephone: 717-764-7700
Facsimile: 717-764-4129
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HEAT FLOW METER THERMAL TRANSMISSION TEST REPORT

Report No.: I6638.01-116-25

Rendered to:

BAMCORE, LLC
Windsor, California 95492

PRODUCT TYPE: Bamboo Panel

SERIES / MODEL: BAMCORE

SPECIFICATION: ASTM C518-17, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

Test Completion Date: 07/31/18
Report Date: 08/17/18

1.0 Report Issued To: BamCore, LLC
5900 Pruitt Avenue #110
Windsor, California 95492

2.0 Test Laboratory: Intertek - ATI
130 Derry Court
York, PA 17406
717-764-7700

3.0 Project Summary:

3.1 Product Type: Bamboo Panel
3.2 Series/Model: BAMCORE
3.3 Compliance Statement: Results obtained are tested values and were secured by using the designated test method. The testing conforms with all requirements of the referenced specification with the exception that results are reported in English units. Test specimen description and results are reported herein.
3.4 Test Date: 07/30/2018 and 07/31/2018
3.5 Test Record Retention End Date: All test records for this report will be retained until July 30, 2022.
3.6 Test Location: Intertek - ATI test facility in York, Pennsylvania.

3.7 Test Sample Source: The test specimen was provided by the client. Representative samples of the test specimen will be retained by Intertek - ATI for a minimum of four years from the test completion date.

4.0 Test Method:

ASTM C518-17, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus

5.0 Test Conditions:

	35 Mean	75 Mean	
5.1 Cold plate temperature:	0	50	°F nominal
Warm plate temperature:	70	100	°F nominal
Mean specimen temperature:	35	75	°F nominal
Average Temperature Gradient:	70	50	°F/inch

5.2 Orientation of Heat Flow Meter Apparatus: Vertical heat flow (Down)
5.3 Specimen Configuration: Single horizontal specimen
5.3 Metering: 4" x 4" heat flux transducer on warm side plate

6.0 Test Specimen Description:

6.1 Specimen Test Size: 12 inches x 12 inches
Compressible Sample: No

6.2 Specimen Construction: The test specimens were provided by the client as sheets of material approximately 1-1/4" x 48" x 96". A 12" x 12" section was cut from a full sheet of material and tested.

7.0 Test Results:

7.1 Product Results BAMCORE

	Sample 1 35 Mean	Sample 1 75 Mean
Test Specimen ID	1	2
Test Duration (minutes)	50	50
Average heat flux (Btu/hr·ft2)	39.17	29.62
Average thermal conductance - C (Btu/hr·ft2·°F)	0.561	0.593
Average thermal resistance -R (hr·ft2·°F/ Btu)	1.78	1.69
Average thermal resistance - R_{si} (m2·K/W)	0.31	0.30
Average thermal resistivity -r (hr·ft2·°F/ Btu-in)	1.39	1.32
Apparent thermal conductivity - k (Btu-in/hr·ft2·°F)	0.718	0.758
Specimen Average Thickness (inches)	1.280	1.280
†Specimen Average Density (Lbs/Ft^3)	42.39	42.39

Notes: †The density of the sample was determined by dividing the average weight of the sample by its volume. The weight was measured using a calibrated scale and the volume was determined by measuring the length, width and height of the sample.

7.2 Uncertainty: Less than 3%, per ANSI/NCSL Z540-2-1997 Type B.

8.0 Calibration:

8.1 Material Types Used: NIST Standard Reference Material 1450d, Fibrous Glass Board, Serial Number 357
Dated January 20, 2012, no expiration

Material Thermal Resistance:
75 Mean = 4.39 $hr \cdot ft^2 \cdot °F/ Btu$
35 Mean = 4.75 $hr \cdot ft^2 \cdot °F/ Btu$

Intertek - ATI will service this report for the entire test record retention period. Test records that are retained such as detailed drawings, datasheets, representative samples of test specimens, or other pertinent project documentation will be retained by Intertek - ATI for the entire test record retention period. The test record retention end date for this report is July 30, 2022.

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Attachments (pages): This report is complete only when all attachments listed are included.
Appendix A: Photos (1)

Revision Log

Rev. #	Date	Page(s)	Revision(s)
.01R0	8/17/2018	All	Original Report Issue

Pictures of the samples tested are enclosed in this Appendix

Appendix A
I6638.01-116-25

Test Sample

THERMAL CONDUCTIVITY OF ENGINEERED BAMBOO

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DOI 10.1007/s10853-015-9610-z

Thermal conductivity of engineered bamboo composites

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Abstract Here we characterise the thermal properties of engineered bamboo panels produced in Canada, China, and Colombia. Specimens are processed from either Moso or Guadua bamboo into multi-layered panels for use as cladding, flooring or walling. We utilise the transient plane source method to measure their thermal properties and confirm a linear relationship between density and thermal conductivity. Furthermore, we predict the thermal conductivity of a three-phase composite material, as these engineered bamboo products can be described, using micromechanical analysis. This provides important insights on density-thermal conductivity relations in bamboo, and for the first time, enables us to determine the fundamental thermal properties of the bamboo cell wall. Moreover, the density-conductivity relations in bamboo and engineered bamboo products are compared to wood and other engineered wood products. We find that bamboo composites present specific characteristics, for example lower conductivities—particularly at high density—than equivalent timber products. These characteristics are potentially of great interest for low-energy building design. This manuscript fills a gap in existing knowledge on the thermal transport properties of engineered bamboo products, which is critical for both material development and building design.

Introduction

Bamboo is a rapidly growing and renewable material with increasing interest for its use as a structural building material [1–5]. As a natural, cellulosic material, bamboo is comparable to timber; however, bamboo species belong to the family of grasses and differ from timber in both gross morphology and cellular structure: a comparison is given in Fig. 1. Due to the highly axially oriented cellulose microfibrils within bamboo cells, and cells that form longitudinal vascular bundles within ground tissue (parenchyma), bamboo is stronger in axial tension and axial compression than timber [1]. To take advantage of this, various advancements have been made over the past decade in the development of engineered bamboo products, such as laminated bamboo, bamboo scrimber, and bamboo-oriented strand board [6], in some ways mimicking the fundamental concepts behind engineered wood products [7], for the rapid construction of low-embodied energy buildings.

Characteristics of bamboo: thermal properties

Assessment of the thermal properties of engineered bamboo composites and a comprehensive understanding of how their properties can be tailored (for example by altering the structure of the composite) are critical for the design of buildings constructed with them. Thermal conductivity governs the heat transfer rate through the bulk material during processing and therefore controls heating and cooling processes during manufacture (including drying,

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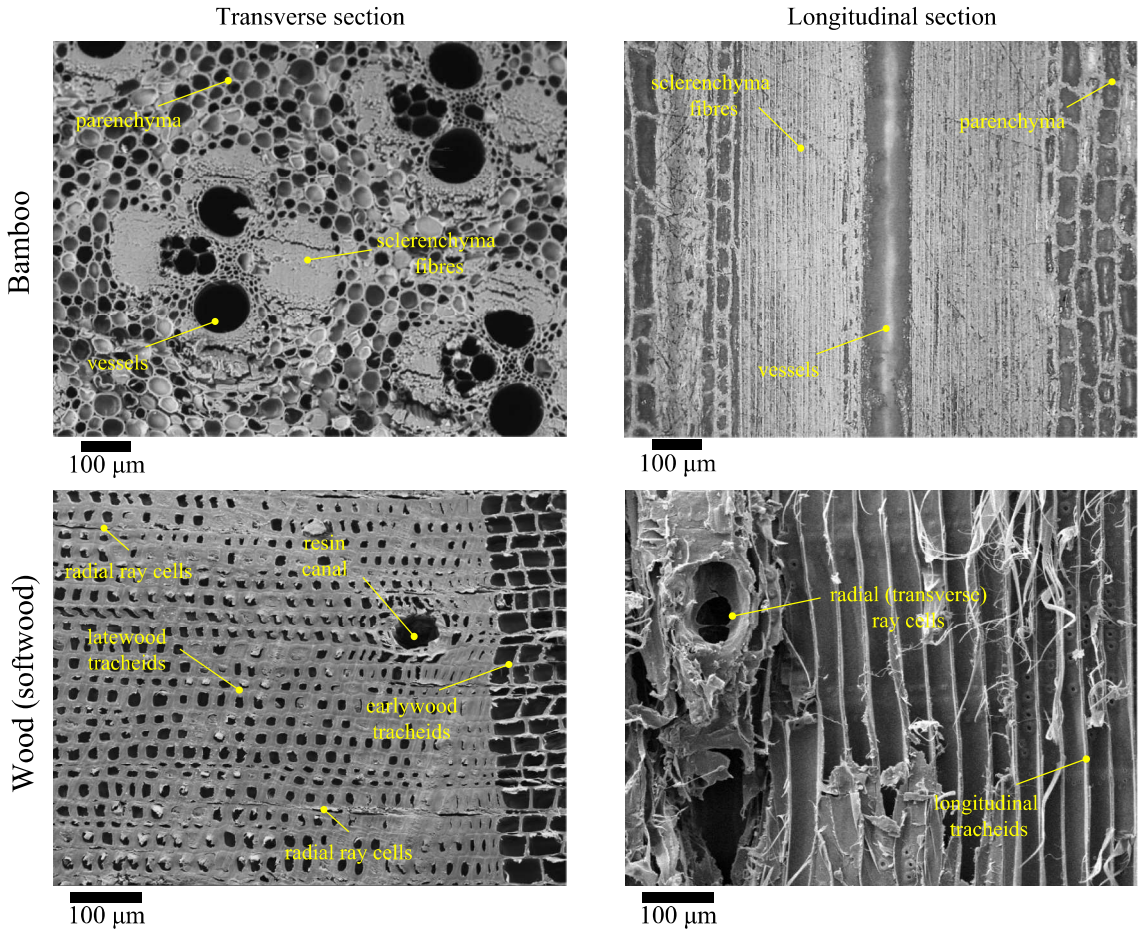


Fig. 1 Bamboo has a more heterogeneous microstructure in comparison to wood (image showing Sitka spruce). In bamboo, vascular bundles, which comprise hollow vessels surrounded by long and thick, fibrous sclerenchyma cells (with secondary cell walls), are embedded in a matrix of brick-like, thin-walled, hollow parenchyma cells (with only primary cell walls). In softwoods, over 90 % of cells are longitudinal tracheids with thickened secondary cell walls; the remaining cells are principally transverse ray parenchyma cells

hot-pressing, and steaming) and determines appropriate adhesive cure rates. With regard to the long-term durability of a building, material thermal properties play an important role in fire safety; thermal conductivity, for instance, dictates the rate of temperature increase through a material and subsequent rate of degradation in mechanical properties under extreme heat.

In terms of building functions, the thermal properties of materials, including conductivity and capacitance, control their environmental performance and thus the energy performance of the fabric, governing heating and cooling of buildings constructed from them. In turn this has a major influence on the carbon emission during lifetime use of the building. Together with the life-cycle analysis of the bamboo composite structure [4], whole life-costing of the building's performance can be derived.

Thermal transport properties of bamboo and engineered bamboo composites are only sparsely reported in the literature. Huang et al. [8] have examined the thermal properties of bamboo culm, and ascribe fluctuations in conductivity as a function of radial location to changes in the culm microstructure (viz. spatial variation in the morphology of vascular bundles and proportion of parenchyma). On the thermal properties of engineered bamboo composites, Kiran et al. [9] have characterised the thermal conductivity of bamboo mat board and Mounika et al. [10] that of bamboo fibre-reinforced composites. While these studies report a correlation between density (or fibre volume fraction) and thermal conductivity, there is a lack of substantial analysis and discussion on the structure–property relations, in particular from a micromechanical modelling perspective. This is in contrast to wood and engineered wood composites whose thermal properties and behaviour have been thoroughly characterised since the studies by MacLean [11], Maku [12], and Kollmann and Malmquist [13, 14] in the early-to-mid 1900s.

Here, we evaluated the thermal conductivity of various engineered bamboo products using a transient technique.

The effect of product type and density, and environment-protective coatings, on panel thermal properties was specifically investigated. Moreover, the experimental results were compared to results predicted from micromechanical models, which considered the engineered bamboo products as three-phase composites. This enabled us to determine constituent material properties that are otherwise difficult to measure (e.g. thermal conductivity of the solid cell wall material in the longitudinal and transverse directions). Furthermore, we could accurately predict the thermal properties of engineered bamboo products based on their density. As a useful comparison, the properties of engineered bamboo composites were benchmarked against engineered wood composites.

Experiments

Materials

Four different engineered bamboo products were examined (see Table 1; Fig. 2):

- Laminated Bamboo is fabricated from strips of bamboo that are processed into rectangular cross sections and thereafter laminated to form a macro-composite.
- Bamboo-Oriented Strand Board is manufactured by compressing bamboo strand elements embedded in a polymer; the strands are aligned in specific orientations for different layers [15].
- Laminated Bamboo Esterilla Sheet comprises mechanically flattened bamboo poles; the finished sheet has visible air gaps.
- Bamboo Veneer Board, which also has a laminate structure, involves the composite assembly of thin bamboo veneers.

With the exception of bamboo-oriented strand board [6], all products are commercially available.

The materials were obtained as 10- to 20-mm-thick panels, 200–400 mm^2. The fibre orientation and layer configuration (including relative thickness of the layers) of the different products is presented in Table 1, and qualitatively visible in Fig. 2. For the products used here, laminated bamboo and bamboo veneer board comprise Moso bamboo (*Phyllostachys pubescens*), while bamboo-oriented strand board and laminated bamboo esterilla sheet of Guadua (*Guadua angustifolia*). Some of the products were also obtained with environmental-protective treatments and external, micro-thickness coatings, as is necessary when using the products for exterior use.

All material samples were conditioned at 60 % relative humidity and ambient temperature for a minimum of 30 days. The moisture content of the samples was measured at approximately 12 % via a moisture content reader (MO220 Extech Instruments Moisture Meter).

Density and volumetric composition

The apparent density ρ_c of the materials was calculated from their mass and apparent volume measured under controlled conditions. This is reported in Table 1.

The volumetric composition of the samples was calculated for three constituent phases: (i) cell wall material, (ii) air, and (iii) polymer matrix (Fig. 3). The polymer matrix weight fraction w_m was obtained from the material

Table 1 Engineered bamboo products specifications

Image in Fig. 1	Product type	Treatment	Sheet size (mm × mm)	Sheet thickness[a] (mm)	Density[a] (kg/m^3)	Number of layers, and their relative orientations and thickness proportions	Manufacturer	Species
(a)	Laminated Bamboo	Uncoated	200 × 200	19.0 ± 0.1	626 ± 1	Three layers (0°, 90°, 0°) orientation. Thickness of (20, 60, 20 %)	Smith and Fong Plyboo (US)	Moso
(b)	Bamboo Oriented Strand Board	Uncoated	300 × 300	11.5 ± 0.3	714 ± 9	No distinct layers. Strand orientation typically 0° ± 30°	University of British Columbia (Canada)	Guadua
(c)	Laminated Bamboo Esterilla Sheet	Uncoated	200 × 200	16.7 ± 0.4	792 ± 32	Three layers (0°, 90°, 0°) orientation. Thickness of (33, 33, 33 %)	Guadua Bamboo S.A. (Colombia)	Guadua
		Indoor	400 × 400	15.1 ± 0.5	713 ± 27			
		Outdoor	200 × 200	15.8 ± 0.1	750 ± 39			
(d)	Bamboo Veneer Board	Indoor	300 × 150	11.3 ± 0.1	960 ± 2	Thirteen layers. Woven structure with equal proportions of 0° and 90° slivers	Anji Chenbao Bamboo Veneer Factory (China)	Moso

Refer to Fig. 1 for images of the products

[a] Mean ± one standard deviation

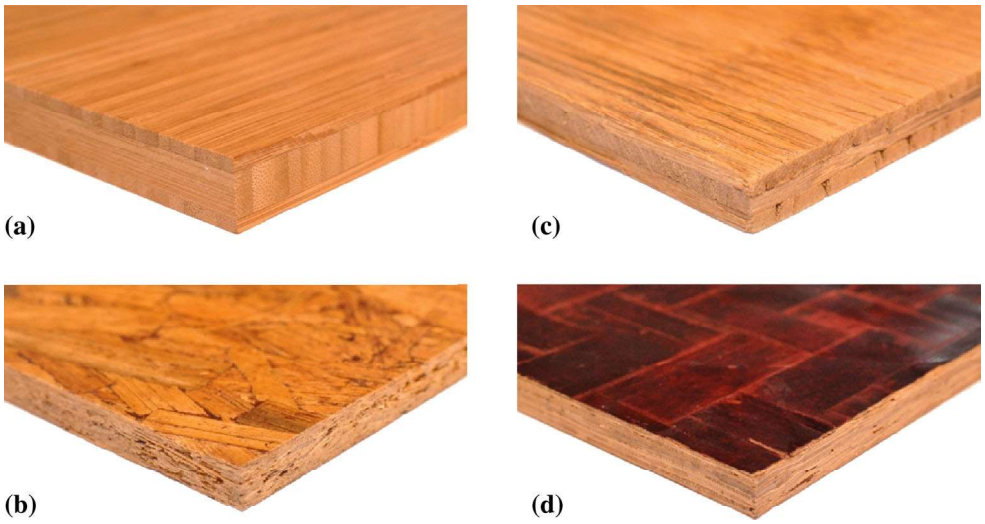


Fig. 2 Surface layer and side view of Laminated Bamboo (**a**), Bamboo-Oriented Strand Board (**b**), Laminated Bamboo Esterilla Sheet (**c**), Bamboo Veneer Board (**d**). Refer to Table 1 for more detail on product specifications

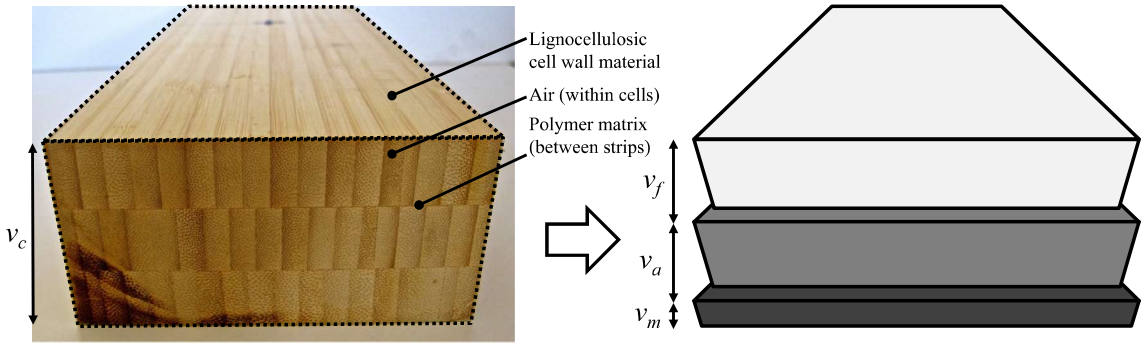


Fig. 3 Schematic illustration of the separation of the engineered bamboo composite material unit volume v_c into three constituent volumes of the solid cell wall material v_f, air within the cells v_a, and polymer matrix v_m. The material volumes are represented as slabs with thicknesses in proportion to their volumetric sizes

manufacturers to range between 5 and 15 wt% with the median at 8 wt%; the wide range is indicative of the inexact manufacturing process employed, particularly in producing bamboo-oriented strand board. Assuming a density ρ_m of 1250 kg/m^3 for phenol formaldehyde [16], a commonly used resin in engineered bamboo composites manufacture [6], the polymer matrix volume fraction v_m was calculated using Eq. 1. Assuming a density ρ_f of 1500 kg/m^3 for the solid cell wall material [17], the volume fraction of the cell wall material v_f and air v_a were subsequently determined using Eqs. 2 and 3. Here, the proportion of protective polymer coating is considered to be part of the polymer matrix.

$$v_m = \frac{\rho_c}{\rho_m} w_m \tag{1}$$

$$v_f = (1 - w_m)\frac{\rho_c}{\rho_f} \tag{2}$$

$$v_a = 1 - v_f - v_m \tag{3}$$

Thermal conductivity measurement

A Hot Disk™ Thermal Constants Analyser, which uses the transient plane source method [18], was employed to measure the thermal conductivity of the various samples. The element/sensor that we used for both transient heating and temperature measurement comprised a Kapton (polyimide) film insulated nickel double-spiral with a radius of 2.0 mm. The sensor was sandwiched between two sample pieces (Fig. 4). To ensure good thermal contact, it was visually established that the sensor was not adjacent to naturally occurring or process-induced air gaps or cracks on the sample surface. All tests were conducted under ambient environmental conditions (20–22 °C).

The experiment was performed by applying a constant current pulse through the sensor to heat the sample by

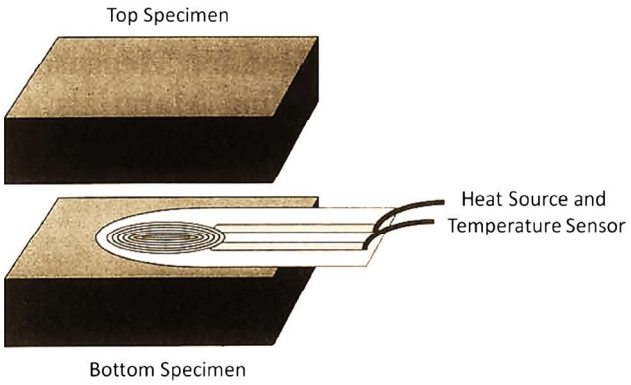


Fig. 4 Experimental setup for transient plane source method using a Hot Disk Thermal Constants Analyser (from [18])

1 °C. The time-dependent resistance variation $R(t)$ is recorded over a sensor with known resistance R_0 and temperature coefficient α, thereby revealing the time-dependent temperature increase of the element ΔT (Eq. 4) [19].

$$R(t) = R_0[1 + \alpha \cdot \Delta T(\tau)] \tag{4}$$

where

$$\tau = \frac{\sqrt{t \cdot D}}{r} \tag{5}$$

with average temperature increase τ as a function of the time measured from the start of the transient heating t, thermal diffusivity D of the sample, and radius r of the Hot Disk. Thermal diffusivity D is equal to the thermal conductivity k over density ρ and specific heat capacity c_p of the sample (Eq. 6).

$$D = \frac{k}{\rho \cdot c_p} \tag{6}$$

To obtain the thermal conductivity k of the sample, both the density and specific heat capacity need to be known. We have obtained the sample density through direct measurement, and the specific heat capacity via a numeric approximation as no verified information is available in the literature. Numeric approximations were made using the estimated thermal conductivity value and diffusivity value given by the Hot Disk analyser software and the measured density of the sample. The specific heat capacity for Moso bamboo composites was estimated at 1.80 ± 0.38 J/kg K which is in agreement with the specific heat capacity of Moso bamboo [8], and with 1.75 ± 0.38 J/kg K for Guadua bamboo composites (for which no value is available in literature).

The measurement time and output power were controlled at 20 s and 100 mW, respectively, resulting in a probing depth of ~5 mm. As the sample dimensions (thickness of 10–20 mm and diameter of at least 45 mm) were much larger than the probing depth, the assumption of an infinite sample domain was met and edge effects were not encountered. Calibration on cast acrylic sheet yielded a thermal conductivity of 0.186 W/m K, which is in agreement with the manufacturer's datasheet value of 0.19 W/m K. The test method repeatability error, obtained through repeated tests on the same point on a laminated bamboo Esterilla sheet, was found to be ~1 %. In addition, preliminary studies carried out to investigate the effect of orientation on thermal conductivity revealed that the variation in the thermal conductivity of a bamboo product measured at different orientations (at the same point) were significantly smaller than variation in thermal conductivity of a bamboo product measured at different points. In essence, point-to-point variation was larger than variation due to changing in-plane orientation. This gave us confidence that although the TPS technique is by nature omnidirectional as a temperature increase is applied in all directions (Fig. 4), the thermal conductivity measurements were being principally made in the in-plane direction, axial to the fibre direction.

Data accessibility

The datasets supporting this article have been uploaded as part of the Supplementary Material.

Results and discussion

Density and volumetric composition

The density of the various engineered bamboo composites ranged from 600 to 1000 kg/m^3, with laminated bamboo exhibiting the lowest density and bamboo veneer board the highest (Table 1). The density of the products depends on the species of bamboo used and the manufacturing process employed. Guadua bamboo products, such as bamboo-oriented strand board and laminated bamboo Esterilla sheet, have a higher density than Moso bamboo products like laminated bamboo and bamboo veneer board. Bamboo veneer board has the highest density entirely due to the manufacturing process: the use of thin veneers which are hot-pressed during assembly and flattened cell walls which reduce air gaps.

The relative proportions of solid cell wall material, air and polymer matrix in the various products are presented in Fig. 5. For each product, two 'extreme' compositions are presented for polymer matrix weight fractions w_m of 5 and 15 wt%. Laminated bamboo exhibited the lowest density and consequently the lowest cell wall fraction (approximately 35–40 vol% of the material). Bamboo veneer board

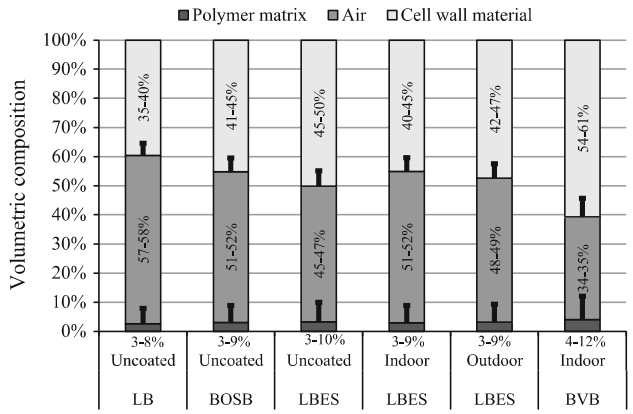


Fig. 5 Volumetric composition of the various engineered bamboo composites: uncoated Laminated Bamboo (LB), uncoated Bamboo-Oriented Strand Board (BOSB), Laminated Bamboo Esterilla Sheet (LBES) that was uncoated, coated for indoor use and coated for outdoor use, and Bamboo Veneer Board (BVB) that was coated for indoor use. *Solid bars* show the volumetric composition for a polymer matrix weight fraction of $w_m = 5$ wt%. *Error bars* indicate the possible range in volumetric composition if polymer matrix weight fraction was $w_m = 15$ wt%. Note that w_m was obtained from the material manufacturers to range between 5 and 15 wt%

has the highest cell wall fraction: up to 60 vol% of the material was accounted for by the cell wall.

Thermal conductivity of different engineered bamboo composites

Hot Disk measurements of the selected engineered bamboo products range between 0.20 and 0.35 W/m K (Fig. 6). The ratios of the median absolute deviation to the median, a measure of dispersion in the measurements, were in the range of 0.01–0.07 for the bamboo products. The dispersion was smallest for laminated bamboo and largest for bamboo-oriented strand board.

We then compared laminated bamboo Esterilla sheet products finished with different coatings for indoor and outdoor use (Fig. 6). We observed that while the indoor coated product had a 17 % lower median thermal conductivity than its uncoated counterpart, the outdoor-coated product had a comparable median thermal conductivity to the uncoated product. While the external coating may influence the thermal properties of the material, it is evident from Fig. 7 that material density has a clear and more substantial influence on thermal conductivity. The lower thermal conductivity of the indoor coated product is therefore more likely due to its lower density (Table 1).

Increasing density typically implies an increase in proportion of solid cell wall material (i.e. relative conductor) and a reduction in proportion of air (i.e. relative insulator); the consequent increase in thermal conductivity is expected. While the strong positive correlation between thermal

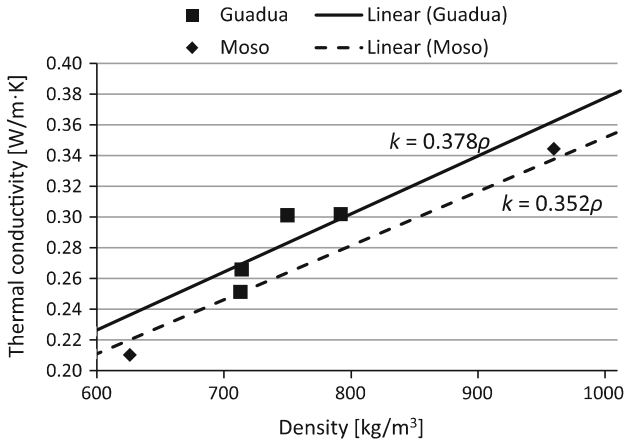
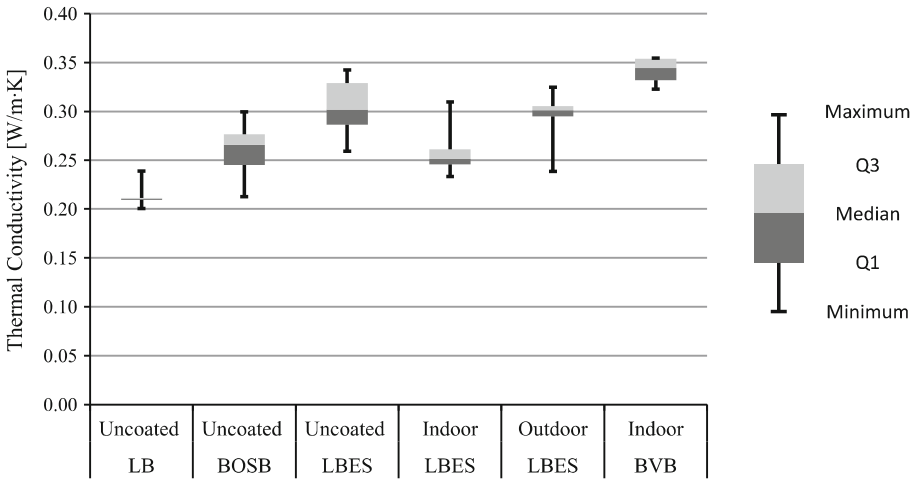


Fig. 7 Thermal conductivity versus density with linear curve fits for Moso (*diamond markers* and *dotted line*) and Guadua (*square markers* and *solid line*) engineered bamboo products. Refer to Supplementary Material for the dataset

Fig. 6 Box plot of thermal conductivity measurements for uncoated Laminated Bamboo (LB), uncoated Bamboo-Oriented Strand Board (BOSB), Laminated Bamboo Esterilla Sheet (LBES) that was uncoated, coated for indoor use and coated for outdoor use, and Bamboo Veneer Board (BVB) that was coated for indoor use



conductivity and density for wood and engineered wood products is well known [11–14, 20], recent studies on bamboo and engineered bamboo products have also shown similar trends [8–10].

Micromechanical analysis for a three-phase composite

Engineered bamboo products, like engineered wood products, have a composite nature with effectively three phases: namely, (i) lignocellulosic cell wall material, (ii) air, and (iii) polymer matrix (e.g. ply-joining adhesive as in laminated bamboo). Composite properties are therefore governed by the properties and volumetric ratios of the constituent phases. In addition, the alignment of one of the phases (specifically the cell wall) leads to parallel and series coupling of the phases when loaded in two planar directions; this results in a difference between longitudinal (axial) and transverse properties of the aligned fibre composite (e.g. engineered bamboo composite). The anisotropic nature of the reinforcing phase (i.e. cell wall) itself, and therefore the difference in longitudinal and transverse conductivity of the cell wall, also contributes to this difference in axial and transverse properties of the composite.

Various micromechanical models have been previously developed to relate various composite bulk properties, including thermal conductivity, to their structure. Most models have been developed for a two-phase composite system, typically where a dispersed reinforcement phase is embedded in a continuous matrix phase. However, it is relatively straightforward to modify these into models for a three-phase composite where a single fibrous phase (viz. cell wall material in the case of engineered bamboo composites) is embedded in a merged, continuous matrix phase comprising two matrices (viz. air and polymer matrix in the case of engineered bamboo composites). Table 2 lists a few models that may be applicable to such a three-phase composite system. As the two matrices are adjacent to each other and can be considered isotropic, the thermal conductivity of the 'merged' matrix phase (or non-fibrous phases) can be obtained by applying the Voigt 'rule of mixtures', based on thermal conductivity of the individual phases and their relative volumetric ratios (Table 2).

To understand density-thermal conductivity relations in engineered bamboo composites, we therefore applied these models to values obtained from the literature and our own experimental data. The 'goodness of fit' of the models was determined from the 'adjusted' non-linear regression coefficient R_a^2, described mathematically in Table 2, which accounted for the number of parameters in the models; $R_a^2 = 1$ denotes perfect fit. Fitting the models in Table 2 to experimental data also enabled the 'back-calculation' of fundamental material properties, such as the axial and transverse thermal conductivity of the solid cell wall. We also compared the behaviour of bamboo and engineered bamboo composites with wood and engineered wood composites, respectively.

Modelling engineered bamboo composites

The two most commonly applied models in the literature are based on the rule of mixtures laws (Table 2): the Voigt model is suitable for conductivity measured parallel to the fibre/cell axis $k_{c\parallel}$ and therefore provides an upper-bound, while the Reuss model is adopted for conductivity measured transverse to the fibre/cell axis $k_{c\perp}$ and therefore provides a lower-bound. Often, the Reuss model provides a conservative estimate for transverse thermal conductivity, and therefore other models may be more appropriate. In literature on wood conductivity [13], an intermediate of the two rule-of-mixtures bounds (using an arithmetic mean, for example) has been previously used to describe transversely thermal conductivity. In such a model, a fitting factor ξ (sometimes referred to as a 'bridge factor') is used as a weighting for the relative contributions of parallel and perpendicular cells. The Halpin–Tsai equations [21], while commonly used to model transverse elastic moduli, may also be used to model transverse thermal conductivity. Springer and Tsai [22] and Zou et al. [23] have also developed models for the transverse thermal conductivities of unidirectional composites, based on a thermal-shear loading analogy and a thermal-electrical analogy, respectively. The Springer and Tsai model is referred to as the C-S model as they assume circular cross section fibre reinforcements in a square-packing arrangement, while the model presented by Zou et al. [23] is referred to as the E-S model as they assume elliptical cross section fibres in a square-packing arrangement.

Axial conductivity As illustrated in Fig. 8, a strong fit (with $R_a^2 \approx 0.97$) was observed when we applied the Voigt upper-bound equation to our experimental data for model constants specified in Table 2. This is despite the fact that the various engineered bamboo products studied here have different fibre orientations (and proportions). This indicated that the transient plane source technique used in this study to measure thermal conductivity properties principally accounted for thermal transfer in the direction parallel to the cell axis. The estimated longitudinal thermal conductivity of the bamboo cell wall material was $k_{f\parallel} = 0.55$–0.59 W/m K. A fully densified bamboo (i.e. where there is no air or polymer matrix and $\rho_c = \rho_f = 1500$ kg/m^3) would therefore have a longitudinal thermal conductivity around $k_{f\parallel} = 0.55$–0.59 W/m K. In Fig. 8, a typical best-fit curve to the experimental data for a single set of input parameters (i.e. single value of

Table 2 Micromechanical models and model constants to predict thermal conductivity of a three-phase composite material, like engineered bamboo composites

	Density, ρ (kg/m^3)	Thermal conductivity, k (W/m K)	Reference
Model constants			
Bamboo cell wall	1500	–	[17]
Air	1.2	0.025	[18]
Polymer matrix	1250	0.145	[16]
Use matrix weight fraction w_m to be 5 % (minimum) or 15 % (maximum)			
Micromechanical models			
Rule of mixtures models			
Voigt (upper-bound) for longitudinal properties		$k_{c\parallel} = k_{f\parallel} v_f + k_m v_m + k_a v_a$	
Reuss (lower-bound) for transverse properties		$\frac{1}{k_{c\perp}} = \frac{v_f}{k_{f\perp}} + \frac{v_m}{k_m} + \frac{v_a}{k_a}$	
Arithmetic mean for mixed orientation properties		$k_c = k_{c\parallel}\xi + k_{c\perp}(1-\xi)$, ξ is a fitting factor	
Halpin–Tsai model (for longitudinal or transverse properties)			
$k_c = k_{nf}\frac{(1+\xi\eta v_f)}{(1-\eta v_f)}$, where $\eta = \frac{\frac{k_f}{k_{nf}}-1}{\frac{k_f}{k_{nf}}+\xi}$, $k_f = k_{f\parallel}$ or $k_{f\perp}$			
ξ is a geometric fitting factor (usually two times the longitudinal aspect ratio for $k_c = k_{c\parallel}$ and $k_f = k_{f\parallel}$ and two times the transverse aspect ratio for $k_c = k_{c\perp}$ and $k_f = k_{f\perp}$)			
C-S model (for transverse properties)			
$k_{c\perp} = k_{nf}\left[1 - 2\sqrt{\frac{v_f}{\pi}} + \frac{1}{B}\left(\pi - \frac{4}{\sqrt{1-B^2\frac{v_f}{\pi}}}\tan^{-1}\left(\frac{\sqrt{1-B^2\frac{v_f}{\pi}}}{1-\sqrt{B^2\frac{v_f}{\pi}}}\right)\right)\right]$, where $B = 2\left(\frac{k_{nf}}{k_{f\perp}} - 1\right)$			
E-S model (for transverse properties)			
$k_{c\perp} = k_{nf}\left[1 - \frac{1}{c} + \frac{\pi}{2d} - \frac{c}{d\sqrt{c^2-d^2}}\cos^{-1}\left(\frac{d}{c}\right)\right]$, where $c = \sqrt{\frac{\pi\xi}{4v_f}}$, $d = \xi\left(\frac{k_{nf}}{k_{f\perp}} - 1\right)$			
ξ is a geometric fitting factor (usually the reciprocal of the transverse aspect ratio)			
Other equations			
Conductivity of merged matrix phase			
In the above models, the conductivity of the merged (air and polymer) matrix phase is obtained using:			
$k_{nf} = \frac{k_m v_m + k_a v_a}{v_m + v_a}$			
This is obtained through the application of the Voigt rule of mixtures on the adjacent air and polymer matrix phases			
Converting between density and volumetric composition			
For a given material density ρ_c (ranging between nil and the density of the bamboo cell wall), and a fixed matrix weight fraction w_m (5 or 15 %), the volumetric composition can be determined through Eqs. 1–3			
The obtained volumetric composition can then be used as inputs, alongside the model constants, to the micromechanical models.			
Paired values of material density ρ_c and thermal conductivity k_c are therefore obtained at the same volumetric composition			
Determining the 'adjusted' non-linear regression coefficient R_a^2			
The non-linear regression coefficient R^2 is obtained from $R^2 = 1 - \frac{SSE}{SST}$, $SSE = \sum_i (y_i - f_i)^2$, $SST = \sum_i (y_i - Y)^2$, where y_i is the observed value of thermal conductivity, Y is the mean of the observed values, and f_i is the estimated/predicted value of thermal conductivity (obtained from the model).			
The 'adjusted' non-linear regression coefficient R_a^2 accounts for the number of input parameters p, and the sample size n. $R_a^2 = 1 - \frac{SSE}{SST}\frac{n-1}{n-p-1}$			
Notation and information on Supplementary Material in table footnote			
k, ρ and v denote thermal conductivity, density and volume fraction, respectively. Subscripts c, f, m, a, and nf denote composite, cell wall material, polymer matrix, air, and non-cell wall material (i.e. polymer matrix and air), respectively. Subscripts $\parallel$ and $\perp$ denote parallel and transverse to the fibre direction, respectively			
Please refer to Supplementary Material to see the template for modelling of the experimental data through the various models, including how density is converted to volumetric composition, how the conductivity of the merged (air and polymer) matrix phase is determined, and how the 'adjusted' non-linear regression coefficient R_a^2 is obtained			

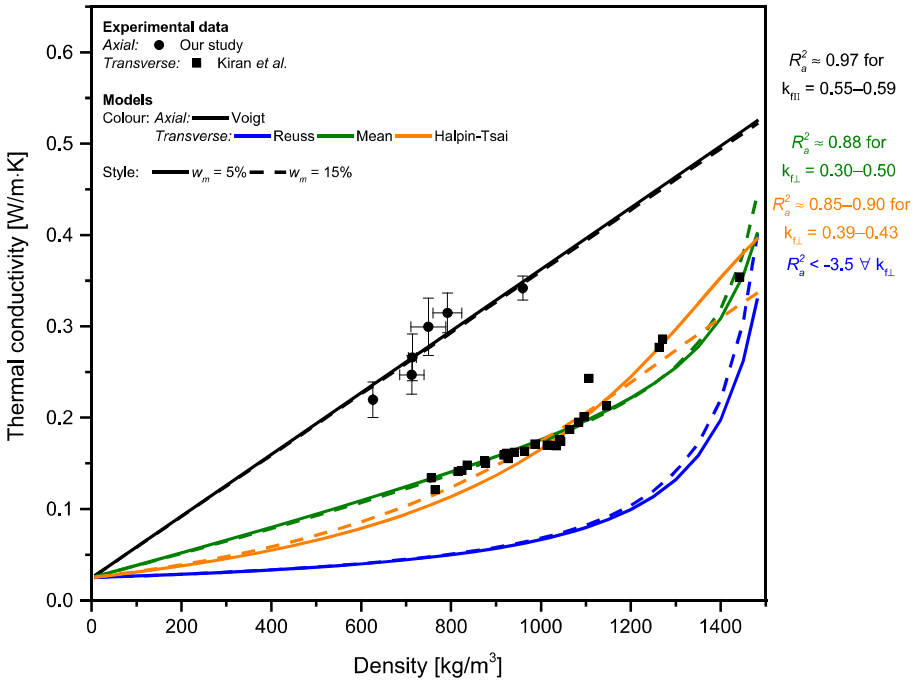


Fig. 8 The effect of density on thermal conductivity of engineered bamboo composites. Our experimental data on longitudinal (axial) conductivity is presented as filled dots, and data on transverse (through-thickness) thermal conductivity data from Kiran et al. [9] is presented as filled squares. Curves represent micro-mechanical models that have been fitted to the experimental data. Solid and dashed lines represent estimations for an assumed polymer matrix weight fraction of 5 and 15 wt%, respectively. The colours are indicative of the model used: *black* Voigt model, *blue* Reuss model, *green* arithmetic mean model, and *orange* Halpin–Tsai model. The fit of the curves to the experimental data is disclosed by the 'adjusted' non-linear regression coefficient R_a^2. A typical best-fit curve is shown for an example estimated best-fit axial or thermal conductivity; for reference, the range of parameter values (i.e. axial and transverse bamboo cell wall thermal conductivity) that would yield a family of best-fit curves have been presented next to the curve. Refer to Supplementary Material to see the template for modelling of the experimental data, including how R_a^2 is obtained (Color figure online)

longitudinal thermal conductivity of the cell wall) is shown; for reference, the range of parameter values (i.e. axial and transverse bamboo cell wall thermal conductivity) that would yield a family of best-fit curves have been presented next to the curve.

Notably, applying the Halpin–Tsai equation to the experimental data also yielded similar values for the longitudinal thermal conductivity of the solid cell wall material. For the Halpin–Tsai equation, the geometric fitting factor ξ was based on an average longitudinal cell aspect ratio of 35–90, which in turn was calculated based on aspect ratios for sclerenchyma fibres (vascular bundles) and parenchyma cells of 100 [24] and 2 [25], respectively, and noting that sclerenchyma fibres form 35–90 % of the solid cell wall material [25]. The results of the Halpin–Tsai equation are not plotted on Fig. 8 as they coincided with the Voigt upper-bound equation; the reader is referred to the Supplementary Material excel file to access this data.

As there is a strong, well-predicted relationship between density and longitudinal thermal conductivity for a range of engineered bamboo composites, it is possible to predict the longitudinal thermal conductivity of an engineered bamboo composite based on a measured apparent density.

It is interesting to note from Fig. 8 that over the density range studied (i.e. 600–1000 kg/m^3) the ratio of longitudinal thermal conductivity to density is constant. This suggests that the product of specific heat capacity and longitudinal thermal diffusivity of engineered bamboo composites must also be constant (around 0. 34 mW m^2/kg K) over this density range.

Transverse (through-thickness) conductivity Kiran et al. [9] have previously measured the transverse (through-thickness) thermal conductivity of a specific category of engineered bamboo composites (namely, bamboo mat board) for a range of densities. The bamboo mat boards were produced by hot-pressing multiple woven mats of bamboo slivers that were soaked in resin. Comparing these results with our data, it was evident that at the same density, the longitudinal (axial) conductivity $k_{c\parallel}$ of engineered bamboo composites was 2.0–2.6 times higher than the transverse (through-thickness) conductivity $k_{c\perp}$ (Fig. 8).

Applying the relevant micromechanical models in Table 2 to the results from Kiran et al. [9], we firstly found that the Reuss model was an inappropriate fit to the data ($R_a^2 < -3$) for all inputs of transverse thermal conductivity

of the cell wall (Fig. 8). This suggests that a simplistic series model is unsuitable for bamboo and engineered bamboo composites. This is most likely because the cells are not entirely dispersed in the matrix (cell walls are interconnected through a pectin-rich middle lamella), and furthermore there is a mix of parallel and transverse (series) cell walls. While the C-S and E-S models were also a poor fit to the data with $R_a^2 < 0.4$ for all inputs of transverse thermal conductivity of the cell wall, the arithmetic mean (between the Voigt upper- and Reuss lower-bound) and the Halpin–Tsai model were found to be more suitable with $R_a^2 \approx 0.9$ (Fig. 8). The arithmetic mean model was based on the previously determined longitudinal cell conductivity k_{fII} of 0.55–0.59 W/m K, transverse cell conductivity $k_{c\perp}$ of 0.30–0.50 W/m K and bridge factor ξ of 0.35–0.40. The bridge factor, which describes the relative proportions of parallel and series cell walls, is revealing, in that it strengthens the argument of why the Reuss (series-only) model is not an appropriate fit to the data. However, in this arithmetic mean model, the wide range of possible transverse cell conductivity was due to the few data points at higher densities (>1200 kg/m^3), only above which the Reuss lower-bound has a more notable contribution (relative to the Voigt model). In contrast, the Halpin–Tsai model provided a narrower estimate of the transverse cell conductivity in the range of 0.39–0.43 W/m K. For the Halpin–Tsai model, longitudinal cell conductivity k_{fII} of 0.55–0.59 W/m K and a fitting factor ξ of 2–3 (based on a transverse cell aspect ratio of 1.0–1.5) were used. We estimated, therefore, that a fully densified bamboo would have a transverse thermal conductivity of $k_{f\perp} = 0.39$–0.43 W/m K.

Comparison with wood and engineered wood composites

As bamboo is often considered as an alternative to wood, and indeed analogous to wood with respect to materials development, testing standards, and end-use (but importantly not in microstructure and mechanical behaviour) [1, 2, 7], a comparison of the thermal properties of engineered bamboo composites with engineered wood composites is useful.

There is substantial amount of the literature on the thermal transport properties of wood and engineered wood composites that is based on extensive experimental data and semi-empirical modelling [11–14, 20]. The researchers have primarily used the rule-of-mixtures models to describe density-conductivity relations Voigt model for longitudinal properties, and arithmetic mean model with the bridge factor ξ ranging from 0.14 to 0.58 for transverse properties. They have observed similar trends, and extracted the same fundamental material properties as we have in this study.

Figure 9 presents a comparison of the density-conductivity relationship in wood and wood products and bamboo products. It was observed that at the same density, bamboo products had the same or lower thermal conductivity in comparison to wood. In a building context, such engineered bamboo composites would therefore perform better as thermal insulants. This is particularly pronounced at high densities—and thus higher levels of volumetric capacitance. Engineered bamboo composites may hence provide useful alternatives to timber components where thermal mass is desirable for environmental performance.

Assuming the density of the lignocellulosic cell wall in wood to be 1560 kg/m^3, Maku [12] find the longitudinal and transverse thermal conductivity of the cell wall in wood to be $k_{fII} = 0.654$ W/m K and $k_{f\perp} = 0.421$ W/m K. Similarly, Kollmann and Malmquist [13, 14] find the longitudinal and transverse thermal conductivity of the cell wall in wood to be $k_{fII} = 0.628$ W/m K and $k_{f\perp} = 0.395$ W/m K. Comparing these results with bamboo, for an assumed density of 1500 kg/m^3, we found that the longitudinal conductivity of the bamboo cell wall ($k_{fII} = 0.55$–0.59 W/m K) was lower than that of that wood cell wall, but the transverse thermal conductivity of the bamboo cell wall ($k_{f\perp} = 0.39$–0.43 W/m K) was similar to that of wood cell wall. The values for wood and bamboo are in a similar range as the chemical composition of the cell walls in wood and bamboo are quite similar—

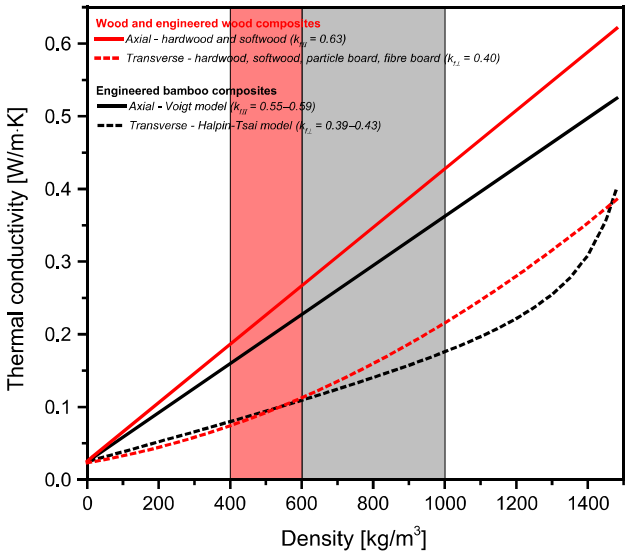


Fig. 9 Comparison of the typical density-conductivity relationship in engineered bamboo composites (*black curves*) and engineered wood composites (*red curves*) in the axial (*solid curves*) and transverse (*dashed curves*) directions based on experimentally verified models. The shaded regions represent the typical density range in which the products are commercially available, with engineered wood composites available in the range of 400–600 kg/m^3 and engineered bamboo composites in the range of 600–1000 kg/m^3 (Color figure online)

they comprise the same organic polymers (cellulose, hemicelluloses, lignin and pectin), albeit in different proportions.

Here, we note that these are calculated/estimated values of the 'average' conductivity of the solid cell wall material. These do not distinguish between intra-cell variations in conductivity (e.g. between the middle lamella, and different cell wall layers) nor the difference in conductivity of different cell types (e.g. parenchyma and sclerenchyma fibres in bamboo). While it would be interesting to compare these estimations with measurements of the single cell wall thermal conductivity, a suitable experimental technique is not available in the literature. Recently, Vay et al. [26] have used scanning thermal microscopy to qualitatively assess the local variability in thermal conductivity at the cell wall level. While they do observe a clear qualitative difference in the conductivity of the different cell wall layers (viz. S1 and S2 secondary layers, and the middle lamella) and anatomical directions (i.e. longitudinal vs. transverse to cell axis), they are unable to measure values.

Evidently, the ratio of longitudinal to transverse thermal conductivity of both engineered bamboo composites and engineered wood composites is $k_{c\parallel}/k_{c\perp} = 2.0–2.6$. However, the ratio of longitudinal to transverse thermal conductivity of the wood cell wall ($k_{f\parallel}/k_{f\perp} = 1.55–1.60$) is higher than that of the bamboo cell wall ($k_{f\parallel}/k_{f\perp} = 1.30–1.50$). These findings merit further investigation. The microstructure of wood and bamboo is fundamentally different (Fig. 1): while both wood and bamboo have a cellular nature, cells in bamboo are principally axially oriented (as in a unidirectional composite) [25], while in wood some cells (viz. ray cells) are aligned in the radial/transverse direction. One would expect, therefore, that the longitudinal cell conductivity in bamboo would be higher (due to better cell alignment), while the transverse cell conductivity in bamboo would be lower (due to fewer cells oriented in the transverse direction). Consequently, the ratio of longitudinal to transverse thermal conductivity would be expected to be higher in bamboo than in wood than is currently observed. We do acknowledge that the experimental observation may be the result of the use of simplified models (such as the rule-of-mixtures model) that do not, for instance, account for the complex, hierarchical microstructure of these natural materials. For example, in bamboo, cells and cell walls are not homogenous. Rather, vascular bundles (comprising of hollow vessels surrounded by sclerenchyma fibres with thick cell walls) are embedded in parenchyma cells with thin walls [25]. This heterogeneity in cell types and structure is not reflected in a single estimated characteristic value for the bamboo cell wall thermal conductivity.

Another similarity in the density-conductivity trend in engineered bamboo composites and engineered wood composites is that ratio of longitudinal thermal conductivity to density is constant in both. Maku [12] notes that the product of specific heat capacity and longitudinal thermal diffusivity of engineered wood composites must also be constant (around 0.40 mW m^2/kg K); this is slightly higher than the value we found for engineered bamboo composites. Maku [12] also argues that as the specific heat capacity is not correlated with density in the case of wood, the relationship between density and longitudinal thermal diffusivity of wood and engineered wood composites can be determined through the constant of proportionality. It is possible that this is also the case for bamboo and engineered bamboo composites.

Researchers have noted that the thermal conductivity of wood and engineered wood composites is influenced not only be density, but also by moisture content: conductivity increases by 1–2 % for a 1 % increase in moisture content [27]. The effect of temperature on thermal conductivity of wood is relatively minor: conductivity increases by 2–3 % for 10 °C increase in temperature [12, 27]. Studying the effect of moisture content and temperature on the thermal conductivity of bamboo and engineered bamboo composites would be an important next step forward.

Conclusions

The characterisation of the thermal properties of engineered bamboo products is a crucial step towards their incorporation in building designs that value and aim to harness the environmental benefits of using natural materials. It shows that bamboo composites present specific characteristics, for example lower conductivities—particularly at high density—than equivalent timber products. These characteristics are potentially of great interest for low-energy building design.

The present work characterises the thermal properties of engineered bamboo products for their use in the construction sector. The study utilised the transient plane source method to record the thermal properties and extrapolate the thermal conductivity values of Moso and Guadua engineered bamboo panels.

Our results confirm that thermal conductivity is a structure-dependent property. Specifically, the volumetric composition, reflected by the apparent density, has a well-predicted effect on thermal transport properties. Describing engineered bamboo products as three-phase composites, we applied micromechanical models to understand density-thermal conductivity relations in bamboo and also extract fundamental material properties. Moreover, the density-conductivity relations in bamboo and engineered bamboo products were compared to wood and other engineered wood products.

Future work envisions the use of thermal chambers to evaluate and compare the results presented here. Unlike a Hot Disk Thermal Constants Analyser, which accurately measures the thermal transport properties within a small volume ($\sim$100 mm^3) and short time span ($\sim$1 s), a thermal chamber simulates thermal conditions as found in and around buildings and has become an internationally recognised methodology for characterising specimens. A full-scale specimen testing could elucidate any effects in comparison to small specimens and allow further comparison to timber. Both results would also be useful in modelling of heat transfer in buildings.

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