A High-Performance Rammed Earth Wall System for Cold Climates

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Buildings are responsible for more than 40 percent of global energy used, and as much as one-third of global greenhouse gas emissions.[1] As the cost of energy rises, and rapid urbanization increases, it has become imperative to take advantage of low-cost passive strategies to reduce the energy demand of buildings, improve the resiliency of local communities and contribute to a positive energy future.

The Casa Sanitas prototype, a "healthy home" designed by Pyatt Studio Architecture and Studio NYL|The SKINS Group-Structural Engineers and Façade Consultants, is part of a larger, ongoing rammed earth research project at the Program in Environmental Design at the University of Colorado Boulder, in collaboration with the School of Architecture at Xi'an University of Science & Technology in China. It is the first rammed earth house to be constructed in the city of Boulder, Colorado.

Conceived as a sustainable alternative to the conventional wood-frame houses found across the Colorado Front Range, the Casa Sanitas prototype (*see "Figure 1" images, this page*) is designed to be a "positive energy home" (positive energy homes produce more energy over the course of a year than they use) and combines cost-effective, passive-design strategies that include the high thermal mass of stabilized rammed earth (SRE) walls, natural ventilation and passive solar orientation, with photovoltaic panels, solar thermal hot water and a small ground-source heat pump for radiant heating and cooling.

A key objective of the project is to develop a comprehensive rammed earth case study to help inform a set of "best practices" for rammed earth construction in the colder climates of Colorado, specifically around optimized thermal performance. Another objective is to establish an "applied research" laboratory to educate the community about the design and construction of sustainable, affordable and regionally appropriate housing.

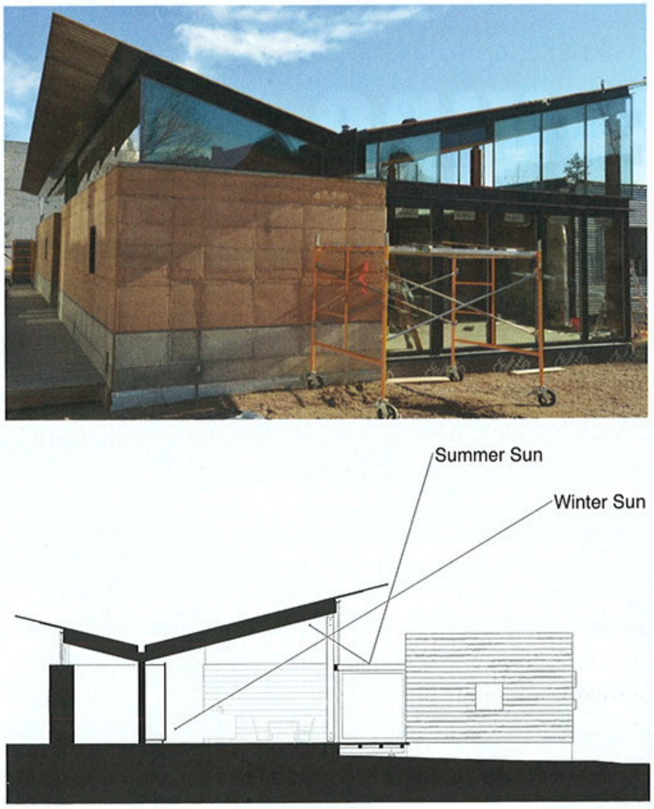
Phase two of the research project will include installing a custom data acquisition system to monitor the house over several years to collect data on the energy performance of the SRE prototype over multiple seasons, as well as improve the energy-modeling capabilities of high-thermal-mass SRE homes in the Colorado Front Range region.

Wall Construction

The SRE walls, which were placed on the north elevation of the house, with partial returns down the west and east elevations, rest on a two-foot-tall base course of concrete. This base course addresses the detrimental effects of moisture on rammed earth, as well as its potential to take on standing water or snow through capillary action at the deck and grade levels. To enhance daylighting, clerestory windows were located between the top of the rammed earth wall and the roof.

Thermal

In terms of being a low-energy and cost-effective building, it was imperative that the exterior building envelope minimize all unwanted heat losses and gains. Moreover, the holistic design of the high-performance building systems demanded it. To simultaneously address the poor thermal conductance and augment the exceptional thermal mass inherent to the SRE walls, four inches of extruded polystyrene (XPS) rigid insulation were sandwiched between the two 12-inch-thick wythes of rammed earth. The clerestories' triple-glazed/



IMAGES: Courtesy of Pyatt Studio Architecture

Figure 1: View of the Casa Sanitas prototype home from the northwest and the building section with solar angles.

Spot-Measured Heat Flux	Spot-Measured U-Factor	Typical Published U-Factor	Calculated Average U-Factor	Measured Average Surface Temp
13.01 W/m^2	1.78 W/°K•m^2	1.6 W/°K•m^2	2.27 W/°K•m^2	5.9 °C
2.29 BTU/h•ft^2	0.31 BTU/h•ft^2•°F	0.28 BTU/h•ft^2•°F	0.40 BTU/h•ft^2•°F	42.62 °F

Table 2: In-situ values of a portion of a stone wall on the Rittenhouse Homestead in Philadelphia.

This method may prove inappropriate for building envelopes with low-conductance values, due to the increased sensitivity and variation of results related to air-film resistance values (the relative high resistance would create much smaller thermal changes in air-film layers).

However, for building envelopes with high-conductance values (such as many historic buildings), this method may help provide better results than relying on standard material assumptions. At the present time, further research involving in-situ testing is being conducted to evaluate the methods to improve the use of thermal imaging in characterizing materials and energy flows through historic-envelope assemblies. JNIBS

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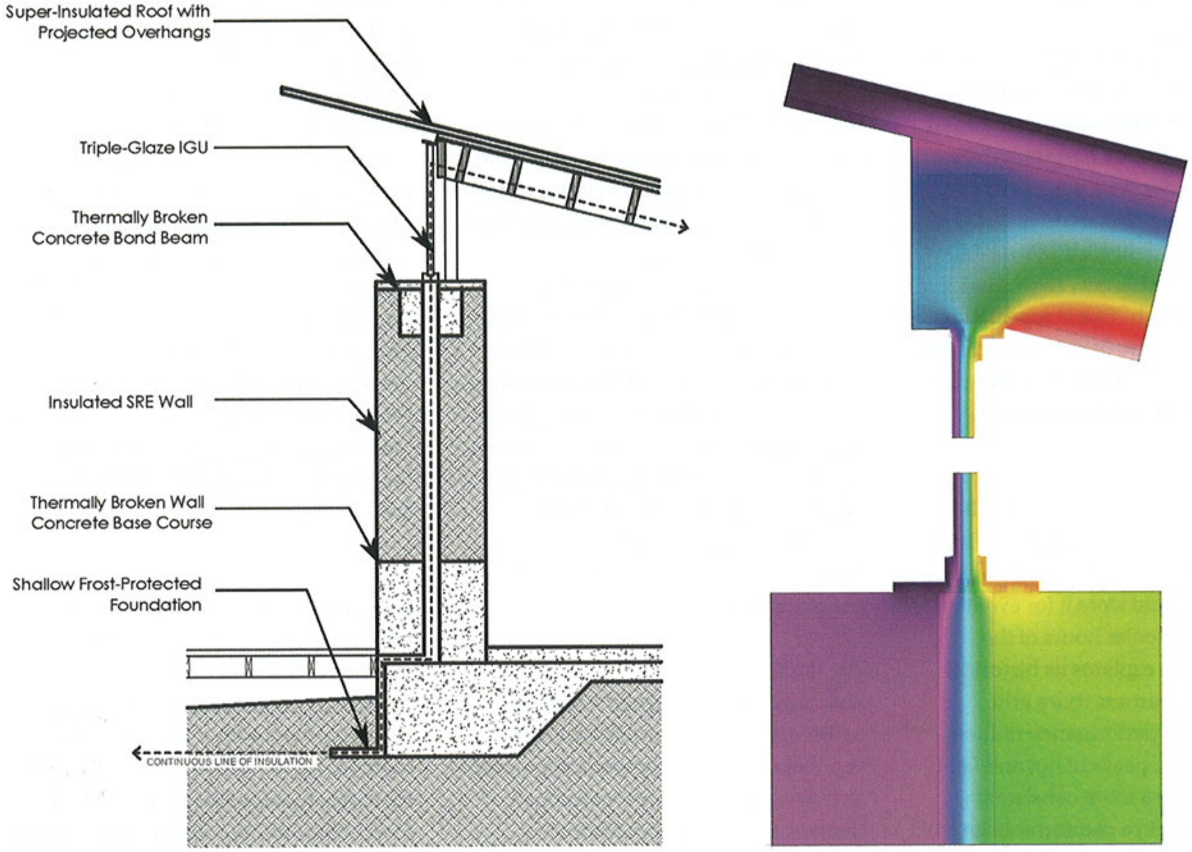

IMAGE: Courtesy of Pyatt Studio Architecture

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Figure 2: The rammed earth wall section (left) is detailed. The thermal analysis images (pictured to the right) show the separation of the interior and exterior at the window head (right, top) and window sill (right, bottom).

double-insulated glass units were tuned for performance demands unique for each building elevation, including solar control on the east and west face, passive solar optimization facing south and super insulation on the north. The U-factors ranged from 0.11- to 0.17-BTU/ft^2-hr-°F. The top of the wall transitions into a super-insulated roof that covers the occupied spaces of the house. In order to protect the walls from the severe weather and solar exposure common in Colorado, large roof overhangs extend three feet beyond the exterior face of the wall and are used as the primary solar control during summer months. The transitions between each of these wall and roof components were designed to minimize thermal bridges, a critical design challenge in the detailing of the envelope. Computer thermal analyses, using the THERM software package, were used to confirm continuous thermal separation across transitions from one assembly to the next (*see "Figure 2" images, above*).

Structural

The soil for the SRE walls is comprised of a local engineered-fill (road base) material blended with local crushed granite (crusher fines) to achieve an even particle-size distribution appropriate for an SRE wall. The soil was stabilized using eight-percent Portland cement by volume, which makes the wall more durable in weathering and freeze/thaw cycles. Since the SRE walls were built two years ago, they have survived severe weather conditions common to Boulder.

The wall is designed for both vertical and lateral loads imposed on the system. The allowable compressive strength of the wall is 500 pounds per square inch (psi), which was confirmed with test cylinders reaching 2,200 psi. Because of the relatively light vertical loads, gravity loads were not of primary concern; rather, the out-of-plane seismic loads and the in-plane seismic and wind loads applied to the wall governed the design. The wall is unreinforced and assumed to have negligible tensile capacity. This led to a post-tensioned system of sleeved threaded rods, spaced at not more than 30 feet apart, to ensure the rammed earth does not exhibit any net tension. The system uses concealed bond beams at the top of each wythe, with post-tensioning rods to pre-compress the rammed earth from the bond beams to the foundation.

Given the significant weight of the wall, the use of a conventional foundation system was not economically feasible. Typical foundations in this region need to be a minimum of 36 inches below-grade for below-frost depths. Instead, the design employed a shallow, frost-protected foundation, which addresses frost-heave concerns by extending XPS rigid foam board insulation 16 inches beyond the foundation wall, and 24 inches beyond at corners. This type of foundation system reduced the amount of concrete required to 0.08 cubic yards per linear foot, and contributed to the overall affordability of the system.

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Rammed Earth Wall Performance

Rammed earth walls have been around for thousands of years. Yet, as simple and historically ubiquitous as rammed earth construction is, the strengths and limitations of the material and its mix design must be understood in terms of its thermal performance, air permeability and moisture resistance, as well as its structural strength. This is especially true when looking at the performance of the wall system in the context of different climates and related energy codes.

Thermal performance

As a material, rammed earth is well-known for its high thermal mass. This attribute allows it to take on heat over a period of time and store it for eventual release during cooler hours of the day (which also explains its historical prevalence in warmer, more arid climates). Such performance reduces the more drastic peaks of hot and cold temperatures to a more consistent range, resulting in a comfortable internal environment and less cooling and heating than would otherwise be required to maintain indoor comfort levels.

Although it provides excellent thermal mass, rammed earth has a relatively high level of thermal conductance, with an R-value of only 0.4-ft²-hr-°F/BTU per inch of cross-sectional thickness. To attain the code-required minimum thermal-performance levels, this project would require an overall wall thickness greater than one meter.

To address this shortcoming and provide the requisite insulation without an unrealistically large cross-section, four inches (R-20) of XPS rigid insulation were sandwiched between the 12-inch interior and exterior wythes of rammed earth. The resulting composite wall system has the benefits of a well-insulated wall, combined with the high-thermal mass of rammed earth construction.

Air infiltration

Casa Sanitas was designed with a fan-assisted, window-controlled natural ventilation strategy. However, as unwanted airflow compromises any envelope's thermal and moisture performance, the building needed to be as air-tight as possible in its closed state. As stabilized earth (much like concrete) will crack over its lifetime, the SRE walls have a post-tensioned system of two 12-inch-thick stabilized rammed earth wythes. Further separating these wythes with a layer of closed-cell XPS insulation (which is an air-barrier material in itself) adds to the air-tightness of the overall profile. Moreover, air infiltration through full-wall cracks is mitigated by overlapping the thick layers inherent in this wall assembly and the project's use of taped, staggered and sealed closed-cell insulation at the center of the wall. In addressing the even greater concerns of transitions between roof, walls and fenestration, all joints were carefully detailed to provide a continuous air barrier across all such junctions.

Moisture resistance

A significant potential drawback in the performance of a rammed earth wall, in terms of the material's resilience and thermal performance, is the effect of moisture. Even with a stabilizer or sealer, rammed earth walls are susceptible to moisture damage. Of greatest concern is freeze/thaw cycling, where any moisture taken into the exterior portions of the wall could freeze, expand and subsequently spall off portions of the rammed earth.

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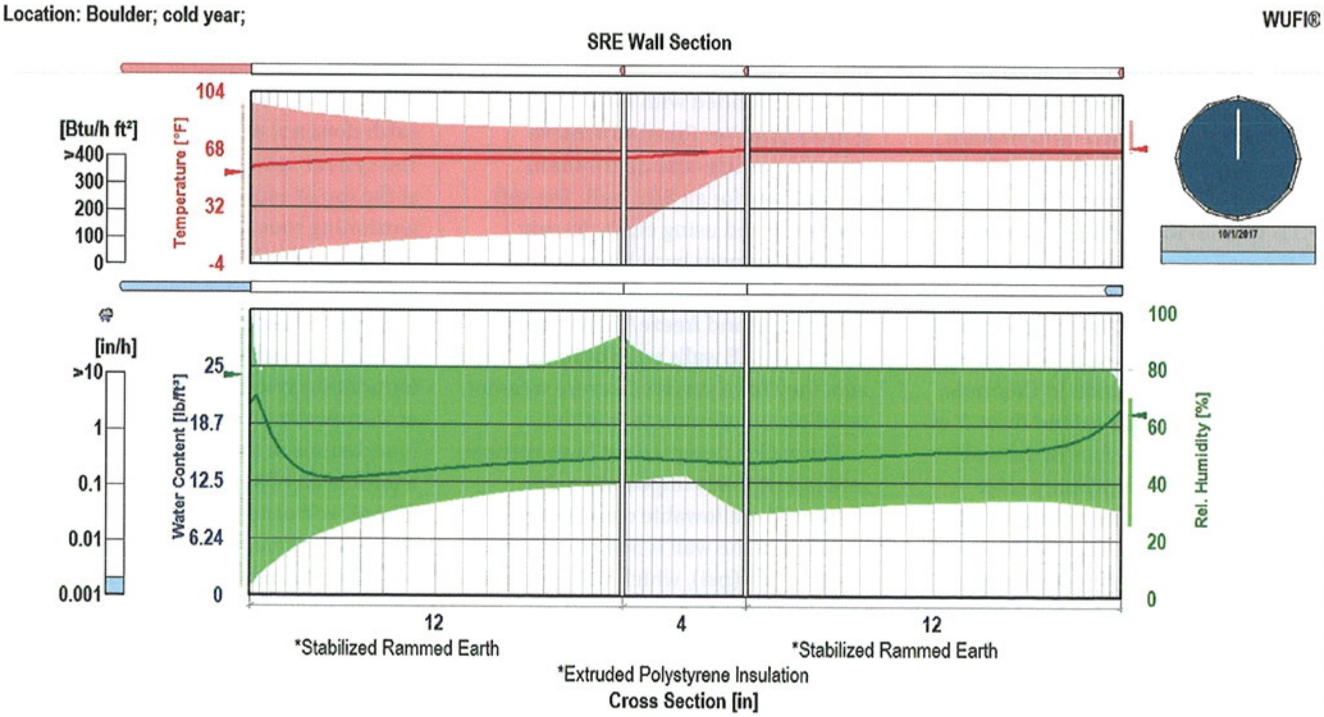

IMAGE: Courtesy of Studio NYL|The SKINS Group-Structural Engineers & Façade Consultants

Figure 3: Hygrothermal models, using site-specific weather data, allowed for a better understanding of the project's thermal-mass performance. As illustrated, the interior temperatures (on the right side of the wall) experienced minimal fluctuation relative to the wide temperature variation of the exterior (left side of the wall). The analyses also eased concerns of moisture build-up in the wall's cross-section.

Given the semi-arid climate and very light-driven rain and dry-snow load that this building will typically experience, it was of less concern than applications in other climates. Still, various moisture-management strategies were employed to prevent water infiltration.

First, the large roof overhang and butterfly roof design shed water away from the walls. For long-term durability, the bottom two feet of the wall were cast-in-place concrete, which offered more resilience at the snow line than an SRE wall. To shed and impede absorption of any moisture that did fall on the wall, a smooth exterior finish was applied on all SRE walls using a 3/8-inch-or-less aggregate soil mixture. Moreover, the eight-percent Portland cement content in the stabilized earth mix further decreased water permeability.

Since the wall performs as a barrier system with the drainage plane on the exterior face, its ability to shed moisture is important. At the few locations where seams between the rammed earth and insulation are exposed, a membrane and metal flashing are employed to address any potential infiltration.

Hygrothermal performance

Due to the complex and variable nature of rammed earth assemblies, a hygrothermal software package, WUFI (from Oak Ridge National Laboratory/Fraunhofer IBP), was used to better understand the behavior of the wall, with respect to the combined effects of heat, air and moisture (HAM). Using actual climate and weather data from Boulder, the wall was put through three years of simulated high and low temperatures, as well as wetting and drying cycles.

By doing so, critical questions about the hygrothermal performance of the wall were evaluated. Typical items of concern, such as the potential of condensation at critical points in the wall's cross-section; water build-up near moisture-sensitive finishes; and potential microbial growth, proved to be non-issues.

At the same time, a concern about moisture build-up in the exterior wythe (where freeze/thaw spalling could result) was evaluated. Fortunately, the wall analysis revealed that the moderate moisture exposure from either interior or exterior sources and the drying potential of the wall were enough to alleviate any significant concerns.

Of additional interest was the thermal performance of the wall. The hygrothermal analysis indicated that, while the exterior temperatures vary from below freezing to more than 100 degrees F, the internal temperature varied only by a couple of degrees throughout the entire year. This data matches those of previous studies of internally insulated composite earth walls, where the thermal-mass effect is readily apparent, even in the presence of the thermal separation of the wythes provided by the insulation. Such performance has been further validated by the house's occupants, who have turned on the heat only once through November, when the outside temperature dropped below 0 degrees F. *(See more detail of the WUFI simulations in "Figure 3" on page 24.)*

In Conclusion

A significant concern with any composite rammed earth wall system is moisture build-up in the interior or exterior wythe, which could cause indoor air quality issues and structural damage. Analyses of the combined effects of heat, air and moisture of an SRE composite wall using hygrothermal software revealed that the drying potential for the system designed for the Casa Sanitas prototype is quite high, given the Colorado Front Range climate. The most recent three-year sample of Boulder's weather data showed that any condensation in the wall assembly was restricted to the outer layers and never surpassed the dewpoint temperature, except in the exterior SRE wythe or within the four inches of XPS insulation. Also, due to the wall assembly's drying potential for the local climate, no moisture accumulated in any layers.

Given these results, a composite wall system that includes four inches (R-20) of closed-cell rigid insulation in the center of a double-wythe, SRE wall assembly is recommended as a "best practice" for contemporary, climate-responsive SRE construction in Boulder. Additionally, the high thermal mass of the interior wythe of SRE is particularly appropriate as part of a low-cost, passive strategy to reduce the energy demand of this prototype home and contribute to a positive energy future. JNIBS

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