Climate Resilient Buildings with Composite Structures

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Abstract

This paper examines the issues associated with constructing a ***climate resilient building*** that combines the latest technical innovations in concrete casting with a traditional frame construction to produce an energy efficient, durable structure which has a much higher degree of resiliency to withstand the ongoing weather impacts of climate change. This new composite structure, with its durable exoskeleton can be designed and engineered to withstand high wind events such as hurricanes and tornadoes, forest fires, floods, and to a high degree, earthquakes. Its durability also has the advantage of increasing the longevity of the structure and minimizing long term maintenance. The process is somewhat different than current standard concrete construction. However, it is designed to use common construction techniques. In this way, it is adaptable to both residential and commercial construction.

The flexibility in form making challenges traditional design and construction processes including the level of resolution in the design, the control of parameters and casting conditions, and the connectivity of building systems. Three case studies in North America: a 1,970 sq. ft. fabric formed concrete residence built in 2009, a 1,800 sq. ft. prototypical passive house, and a 1100 sq. ft. residence constructed in 2017 based on the prototype will be explored. Issues such as constructability, scheduling, and reduced formwork waste will be addressed. Composite structures, which combine both fabric formed concrete and conventional framing methods, will be explored.

1. Schulz residence: fabric formed wall assembly

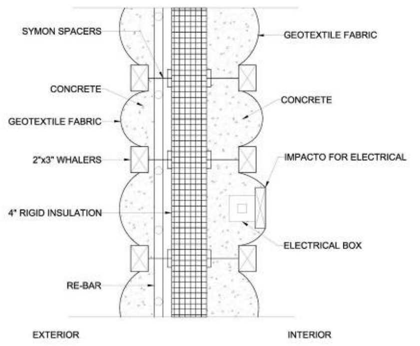
The Schulz House in Waitsfield, Vermont, 2007-2008, is a 2-storey 1,970 square foot residence cast using fabric formwork technology. It serves as a built model for studying the efficiency of using fabric-forming techniques for residential construction in North America (figure 1). An examination of the wall assembly, the casting process, and the construction sequence of the Schulz House indicate at least three primary areas where efficiency of construction could be increased when using fabric formwork for residential construction. 1) The formwork set-up time could be simplified in order to eliminate the higher-risk single pour approach, 2) the number of spacers used to keep the insulation in place could be modified to reduce labor and complexity of installation, as well as cost, 3) the form-work set-up and casting sequence could be modified to allow for flexibility in electrical wiring and interior finishes.

At Schulz the 14-ft high concrete walls are comprised of a "sandwich" system made up of an interior wythe (5") and an exterior wythe (4"). The wythes envelop a 3-inch panel of polyisocyanurate insulation. The formwork, which encompassed the entire thermal envelope of the house, was cast in a single pour. The fabric was supported by the wooden frame and 2" x 3" horizontal wood whalers, which also imprinted a 'pillowed' pattern on the faces of both the interior and exterior wythes. The whalers were held together with high-density plastic form ties. (Figure 2)

Figure 2: View of stripped formwork, Schulz   Figure 3: View of insulation cavity, Schulz

In conventional formwork for concrete casts, a form tie system is engineered based on wall height and other factors. For instance a prefabricated steel formwork panel system (like Symons) uses snap-off ties that hold the form in place. An insulation system such as Thermomass can be inserted into the form system. The insulation has fiberglass tie rods that position the insulation in the wall form and tie the two concrete wythes together after the wall has been poured. At the Schulz house the insulation was held in place with (Thermomass) fiberglass wall ties, placed regularly on a 1’-0” x 2’-0” grid. The wall form was designed to accommodate the standard Thermomass pattern. The horizontal whalers correspond with the fiberglass ties (see Figure 3). The interior wythe is the principal load bearing structural wall and contains the electrical conduit and all structural weldments for steel floor beams. Electrical wiring and boxes must be set into place as part of the fabric formwork and prior to the pour. It would be more efficient to protect work and tradespeople from the elements and place electrical wiring independent of the fabric formwork (see Figure 4).

Figure 4: Wall assembly, Schulz



2. Hybrid wall: Conventional framing and fabric formed assembly

Consideration of the above issues has led to a proposed hybrid wall assembly that streamlines construction and overlap of trades, reduces waste and cost, and capitalizes on the benefits of fabric formwork technology. The theoretical hybrid wall sandwich is based on conventional 2x4 wood framing or light gauge steel framing. As in traditional construction, the framing would be built first and thus provides structural support for an exterior casting plane with fabric. The interior frame acts as ‘stay-in-place’ form for the casting of the exterior concrete wall (see Figure 5). The form for the exterior cast wall would be comprised of composite metal decking placed vertically and tied back to the wood framing with a top stay, or a simpler light gage steel frame filled with insulation that creates a solid form against which the concrete is cast. The proposed hybrid assembly allows for flexibility in the amount, width, and type of insulation used, as well as the thickness of the concrete, and amount of reinforcement required to address higher external forces experienced in high wind or seismic events. The assembly can also achieve passive house insulation requirements and standards.

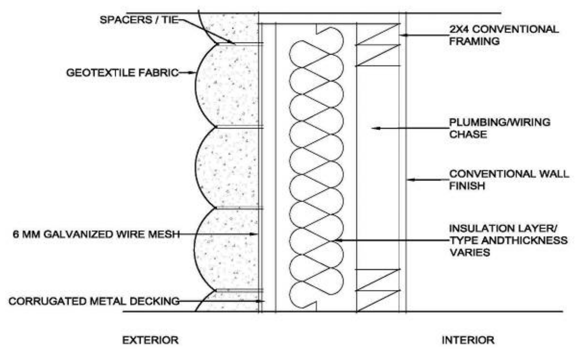


Figure 5: Wall assembly, Hybrid proposal

The issues of eliminating the single-pour approach, reducing the labor intensity surrounding the layer of insulation, and the inflexible and linear construction sequencing at the Schulz House are addressed. The hybrid design enables wall sections to be light weight, pre-fabricated gang forms to be utilized. Once the interior framing is in place, various pre-fabricated sections could be attached. This allows for casting to occur in smaller sections eliminating the complexity of the single pour approach used in the Schulz House. The fabric formed sections could incorporate and capitalize on existing fabric and flexible form techniques and practices, such as impactos and fabric liners. The substantial benefits of using fabric for the exterior form still pertains; the creation of a durable surface with curved sections that add to the strength and beauty to the structure.

Additionally, the labor-intensive placement of the spacers for the insulation at the Schulz House is eliminated. The plane for the form ties is moved to the outside of the building envelope, beyond the insulated cavity. In this hybrid, the fabric gang form can be attached to the structural frame, or the corrugated metal decking, that remains in place. The registration of each tie is either eliminated or simplified. If the corrugated metal decking is used the ¼” screws are the ties and can be placed anywhere along the form wall. This allows for more creativity in designing the fabric restriction, as well as allowing for strategic placement to resist excessive bulging where the hydraulic loads are greatest.

Another notable advantage of this assembly is that the electrical work does not need to be in place before the pour but can be completed indoors once the frame structure is constructed. Additionally, the framing on the interior also facilitates interior casework and cabinetry, in contrast to Schulz, where strapping needed to be used on the interior concrete walls for casework. The hybrid wall assembly allows for more efficiency (and less overlap) during construction with fabric forming. It considers standard building practices in North America which function around the use of wood framing or steel framing. Construction can begin with the framing and the various other trades; concrete work, mechanical and electrical work and interior finish work can happen in a less linear and therefore more flexible sequence. It greatly simplifies the attachment method for casting with fabric and moves away from relying on conventional whalers and stabilizing fiberglass rods for the insulation layer. The hybrid is comprised of traditional elements, framing, corrugated decking, vapor barrier, drill screws that are well understood by local builders. The exterior walls can be cast independently of the interior wall, where certain sections may also be cast for decorative purposes or to address potential flooding issues or increase the strength of the structure.

3. Interior wall: Fabric formed

The proposed integration of the stay in place frame wall liberates the interior finish wall from the cast exterior wall. A second cast for the interior walls could accommodate a variety of functional and aesthetic needs (see Figure 6).

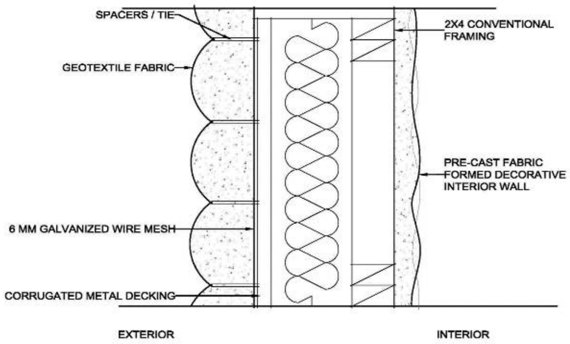
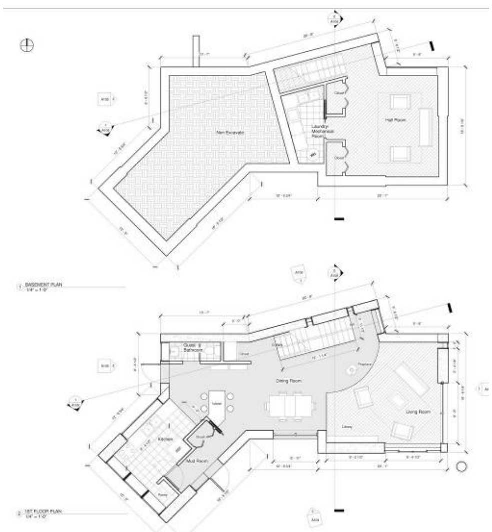


Figure 6: Wall assembly, showing cast interior wall

4. Prototypical passive house

The prototypical concrete passive house for Waitsfield, Vermont, 2015, is a 4 level 1,800 square foot design for a residence that builds on the hybrid wall assembly discussed above aimed at achieving standard practices for a passive house design. In a typical North American passive house, the air barrier is on the outside of the house and the vapor barrier is on the inside. Both require cutting, fitting and taping. In the concrete passive house the exterior cast wall also acts as the air barrier. As described above, the hybrid wall assembly includes an insulation cavity can accommodate 8-10" of insulation with an R-value of 40 that meets or exceeds best practices for a passive house (see figure 5).

The general layout of the proposed passive house is an unfolded volume that opens towards the south and follows multiples sun orientations while addressing compact site conditions. It has a strong vertical connection articulated by a stair volume on the north side. It connects 4 levels. The first two include a basement level with a laundry/mechanical room and a first floor mudroom, kitchen, dining room, living room, and guest bathroom (see figure 7). The second floor has a master bedroom, 2 bathrooms, 2 bedrooms, and common space and above is a green roof (see figure 8).



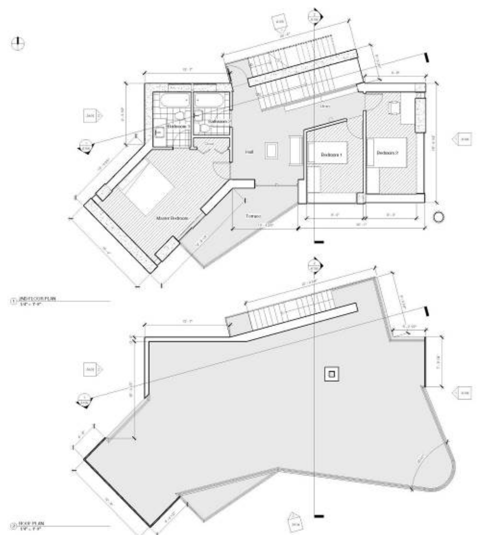


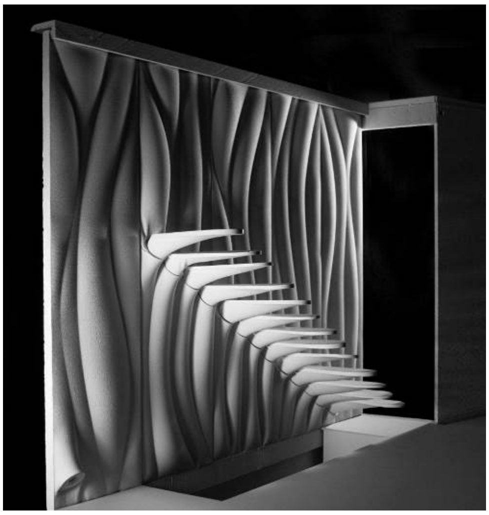
Figure 7: Basement and First Floor

Figure 8: Second Floor and Roof

The northern facade has few openings and an east-facing window illuminates the stair located on the north wall. The rest of the building volume opens up to create two usable outdoor spaces to the east and west; one of these is more public with access to the house and garage; the other is private with access to the kitchen, garden terraces, and a connection to the back door of the garage. The stairs on the north wall are crucial for the design and integrity of the house in order to connect the different levels and provide vertical unity. The stair is designed to attach continuously to the north wall, which acts as a trombe wall. Additionally bathrooms are placed on the north part of the house with a minimum amount of openings (see Figure 9). The eastern facade is comprised of large glazed surfaces oriented towards recreational terraces. To the south and east on the first floor, dining and living areas take advantage of both light and views. The kitchen faces west and has access to a patio for barbecue and gardening. Eastern terraces become an extension of the interior when weather permits, and are protected from solar gain and rain by a fabric cast roof canopy (see Figure 10).

Figure 9: North and West facades
Figure 10: South and East facades

5. Fabric formed trombe wall / stair



Significant design elements with respect to fabric formwork in particular, are cast on interior walls; for instance the trombe wall / stair which is located on the north side (see Figure 11). This fabric formed element is cast on the interior side of the proposed hybrid wall type discussed above. The stair design is conceived as a cantilever structure. Each step is supported at the wall. The prefabricated fabric formed wall incorporates in its surface a casted steel plate, placed at an angle of 45 degrees. The steel plate supports each cast tread of the stair with a welded connection to create structural continuity (see Figures 12 and 13).

Figure 11: North trombe wall / stair

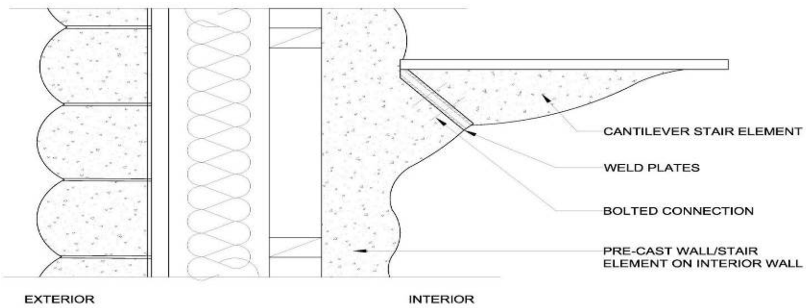


Figure 12: Section through stair / wall

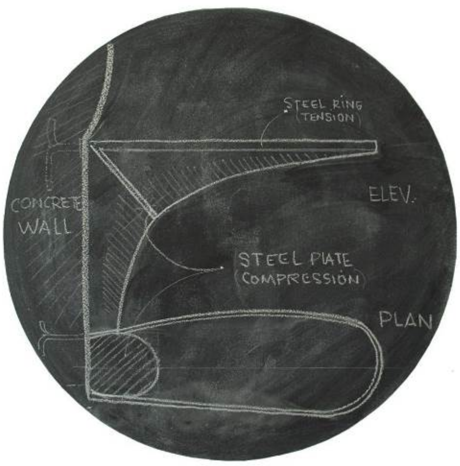


Figure 13: Section / plan sketch of cantilevered stair with steel plate

The flexible mold used to cast the wall and stair elements allows for the smooth transition between the vertical plane of the wall and the horizontal condition of a step. This simple transition between the vertical and horizontal planes is a new opportunity for casting, made possible due to the flexibility of the mold. The prefabricated steps are cast in fabric formed concrete, and the changing profile in section of each step responds intelligently to the structural requirements, adding more material at the connection site and reducing material at the farthest point from the wall. In plan these steps also have an irregular profile, for functional reasons, as they widen where the main circulation happens, and narrow closer to the wall (see Figure 14).

Figure 14: Second Floor and Roof

6. Fabric formed roof canopy and solar shade

The roof canopy on the east side of the passive house has multiple roles; in a utilitarian sense the design of this cantilever creates cover for the large glazed openings in the living/dining room. The canopy overhang mitigates the solar heat gain in summer and allows solar penetration in winter months. The use of fabric formwork allows for an effective and efficient transition between the vertical wall plane and the horizontal roof plane (see Figure 15).

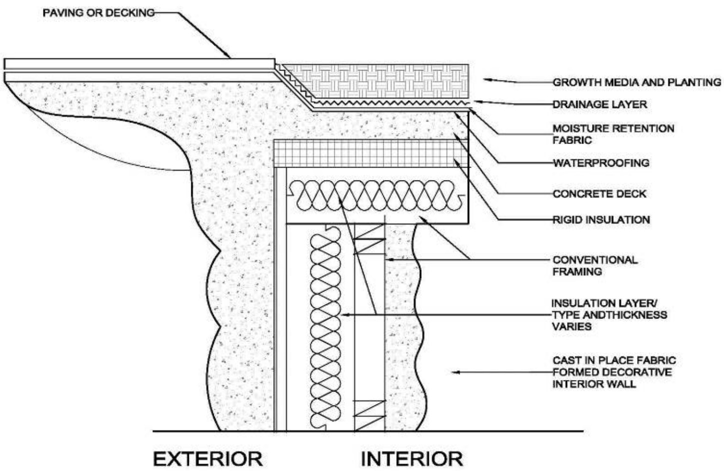


Figure 15: Roof canopy

The cast underside of the cantilever is exposed to create rich ornamentation that is produced by placing bent planes, or splines under a textile in a conventional mold scaffolding. Other patterns can be explored in terms of structural optimization or pure ornamentation. This element is an imagined extension of the internal wall stair panels and the profile was generated using a virtual sun study (see Figure 16)

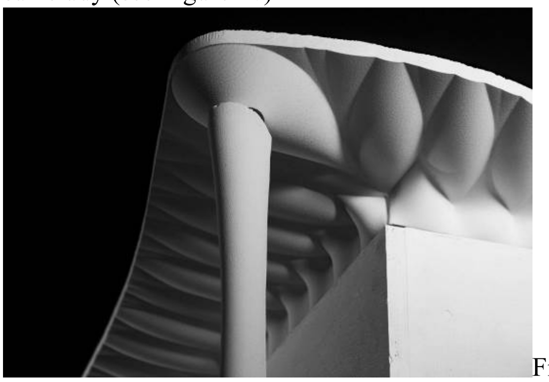


Figure 16: Ornamentation of Roof Canopy

A fabric formed column that anchors and defines the outdoor area beneath supports the corner of the roof canopy cantilever. It is designed as a precast horizontal element using splines (see figure 17).

Figure 17: mold for cast column

7. Development of architectural language and components that can be used at a variety of scales

In addition to the technical aspects of integrating concrete cast with fabric, the prototypical house design explores the potential of a spatial aesthetic unique to fabric formed concrete. The deliberate use of light throughout the house, the craft of the formwork design, and the dual expression of heaviness and fluidity made possible by casting with textiles, creates a distinctive architectural language. The language bridges architecture, structure and sculpture using concrete shaped in flexible membranes. Light is treated as an intangible material to shape space in two significant moments of the house - the *trombe wall / stair* on the north side and the *outdoor space with the fabric cast roof canopy* to the east. Both cast elements are created using fabric formed concrete and have been studied using physical plaster scale models to mimic full-scale construction.

The interior vertical trombe wall / stair of the north is designed as a modulated rectangular tilt up wall. This non-structural layer of the wall is conceived as a sculptural element of the interior space that physically and visually connects the basement, first and the second floor. The wall is intentionally illuminated tangentially with natural light from a vertical window on the southeast. In this way, undulations and deflections of this wall are accentuated, exposing the changing light conditions inside of the house during the day (see figure 18).

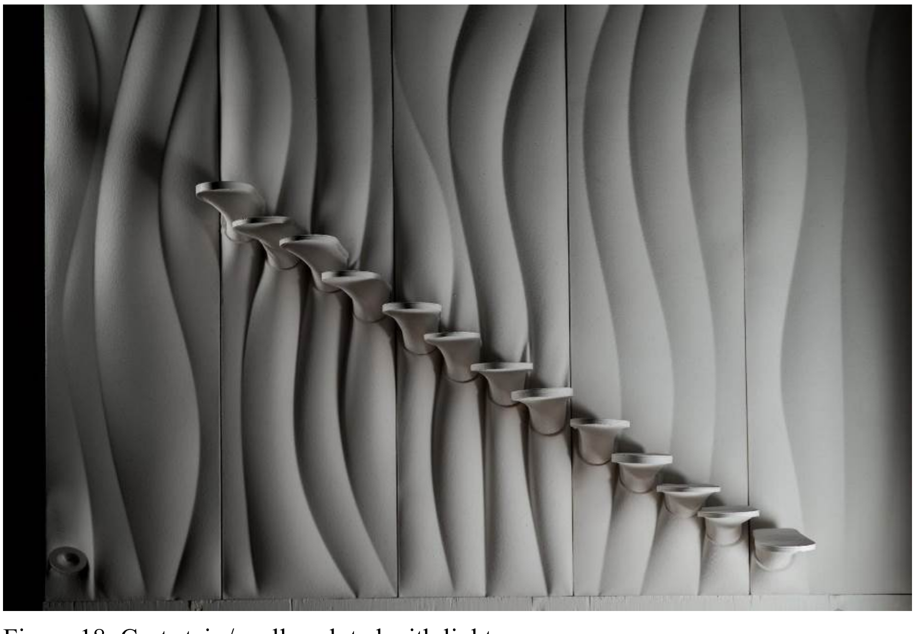
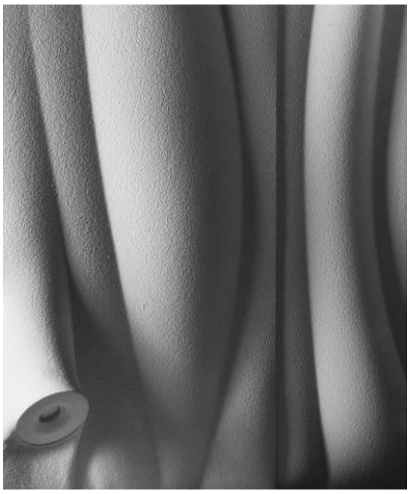


Figure 18: Cast stair / wall sculpted with light

These molds use elements of varying rigidity and flexibility. Plywood offers rigidity, textiles are flexible and splines are a semi flexible material. The introduction of splines as intermediate construction elements is key, because they negotiate the rigidity of the mold (or wood frame in this case) and the 100% flexibility of the textiles, creating smoother geometries resulting in softer transitions between light and shadow (see Figure 19).

Figure 19: Underside of canopy surfaces in light and shadow

The same mold technique that is used for the stair wall can also be inverted and scaled down to create a cast wall with integral lighting (see Figures 20 and 21)



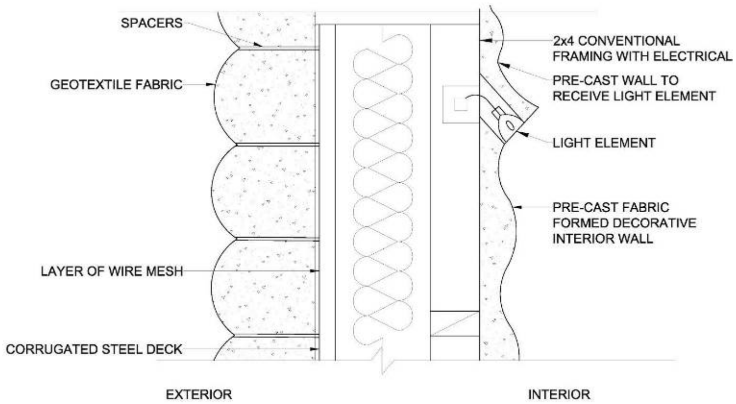


Figure 20:

Figure 21:

8. Application and Testing of Techniques:

In 2017, we applied the new structural techniques to a new 1100 sq. ft. structure built in Waitsfield, Vermont. The house is a 3 bedroom house with two bathrooms. A small vaulted ceiling is incorporated around the stair to take advantage of the western exposure and let warm air escape during the summer months, creating natural ventilation. The stair treads are cantilevered from a cast in place trombe wall. This central concrete interior wall can heat up in the winter as a heat sink. Advances in air to water heat pumps makes if more viable to also include heating tubes in the wall to further increase the heating capabilities of the wall. A large cantilevered porch surrounds the living room and kitchen, providing shade in the summer and a nice integration with the landscape.

Southern elevation

Trombe wall with cantilevered stair

Aesthetically, the exterior concrete is designed to have similar qualities with the surrounding forest and ledge outcroppings. Structurally, the corrugated fluting provides additional lateral strength which is advantageous in high wind areas.

Exterior wall surface

Structural Fluting

A large outdoor terrace on the second floor is accessed by the two bedrooms, and a circular stair is designed to incorporate a future green roof above the second floor.

Outdoor roof terrace

Landing for future spiral stair

The house is constructed on a well-insulated frost protected foundation and structural radiant slab allowing for quick construction and a nice construction area. It also significantly reduced the foundation costs of building on bedrock.

Frost protected foundation with a radiant slab

In this particular case, it was decided to balloon frame the exterior walls with light gage steel studs at 4 foot centers, thus reducing the amount of steel for the stay in place form. The vertical framing was designed to be engaged with the exterior concrete walls and provides additional lateral and compression strength as well as ductility to the walls. This strategy allowed for a reduction in the amount of concrete used in the walls to 4” thick.   The framing for the entire sub-enclosure was completed in seven days. Insulation was strapped to the framing as a thermal break and backing for foam insulation to be sprayed into the wall cavity completing the interior form. The interior was fully insulated and enclosed, allowing for sub-contractors to begin their work. Columns were constructed and the building was ready for the exterior formwork.

Light gage steel structure

Insulation is installed and ready for formwork

The form walls were large gang form panels constructed of 2x4 lumber covered with fabric. Two people can construct and place a form with minimal time and effort. For constructability, the first floor walls were constructed which allow a crew to start the construction of the second floor terrace. Once the first walls were poured, the forms were stripped and lifted in place with a simple hoist located on the second floor roof. The second floor walls were placed, tied and poured along with the second floor terrace with minimal effort. Reinforcement bars were placed on the second floor roof and was quickly ready to pour.

Gang forms being set for second floor wall pour

With the concrete exterior complete, aluminum windows and doors (which require little maintenance and are thermally broken) were installed and the interior finish work could begin in a warm, fully enclosed space. Most of the interior finishes are standard to common house construction. All of the work to make the space warm and inviting such as the stair wall and timber framing had been completed during the forming/framing process. The stair treads were prefabricated and installed using the overhead framing to hoist the treads and bolt them into place.

Interior walls and stair treads hoist attached to framing

Stair treads inserted into the Trombe wall


Interior kitchen and stair


Cantilevered stair and seating area

Decorative cement plaster was troweled on the walls in the kitchen and bathroom showers, providing durable, colored walls and eliminating expensive tile work. A large concrete island was cast in place in the kitchen, and premanufactured cabinets were installed. The advantage of this construction method is that each wall can be easily designed and constructed to address different structural or aesthetic requirements.

Cement plaster wall in kitchen

Cast in place island

For example, in areas prone to flooding, the entire first floor could be constructed of masonry, which is rarely damaged by high water. Or, the interior walls could provide additional structure for seismic activity and high wind events without significant additional effort.

Summary

Utilizing fabric formed concrete assemblies at different scales and finding creative ways to integrate them with local building practices, supports the expression of a distinctive architectural language. The hybrid wall design, which was initially aimed at meeting energy efficiency and climate resiliency design requirements, also provides a separate interior canvas for applying decorative non-structural cast architectural elements at a variety of scales. For instance the casting technique which allows for the transition from a vertical to a horizontal surface in a single cast, such as that used for the roof canopy, could also be used at the scale of the entire envelope to create a thermal break in a passive house design as demonstrated with the third case study. Similarly, the same casting technique could be applied at the scale of a counter-top, a shelving unit, a door overhang, or a fireplace mantle. These fabric cast concrete prototypes lend themselves to a flexible design composition and the development of a comprehensive motif or language of concrete.

The strategies described above are also aimed at developing composite structures that engage both fabric forming and conventional framing methods to simplify and maximize efficiency of labor and construction. Utilizing these methods allows for an efficient thermally broken structure with low air infiltration and lower heating costs. The structural advantages are increased strength, durability and a reduction in concrete volumes and forming materials. There is very little waste in the construction process, and what little there is can be easily recycled. The exterior concrete shell is low maintenance, long lasting as well as being sound and fire resistant. Additionally, the structure is structurally engaged with the foundation resulting in increased resiliency during high wind events such as hurricanes and tornadoes. It is naturally rot and mold resistant which is beneficial in flood prone areas with the use of masonry on the first level. Case study Three also demonstrates that the techniques and methods for building a small residential structure are equally applicable to multi story buildings. Using the same methods of gang forming the exterior walls and attaching them to light gage steel framing, normally used for infill with structural steel, a larger scale building could be constructed in the same fashion. This would increase durability, impact resistance, offer higher resistance to lateral forces, and maintain ductility of a structure. It could also significantly decrease the energy use, and perhaps open up new mechanical methods for heating and cooling our buildings.