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FULCRUM HOUSE – Towards a Sustainable Composite Architecture

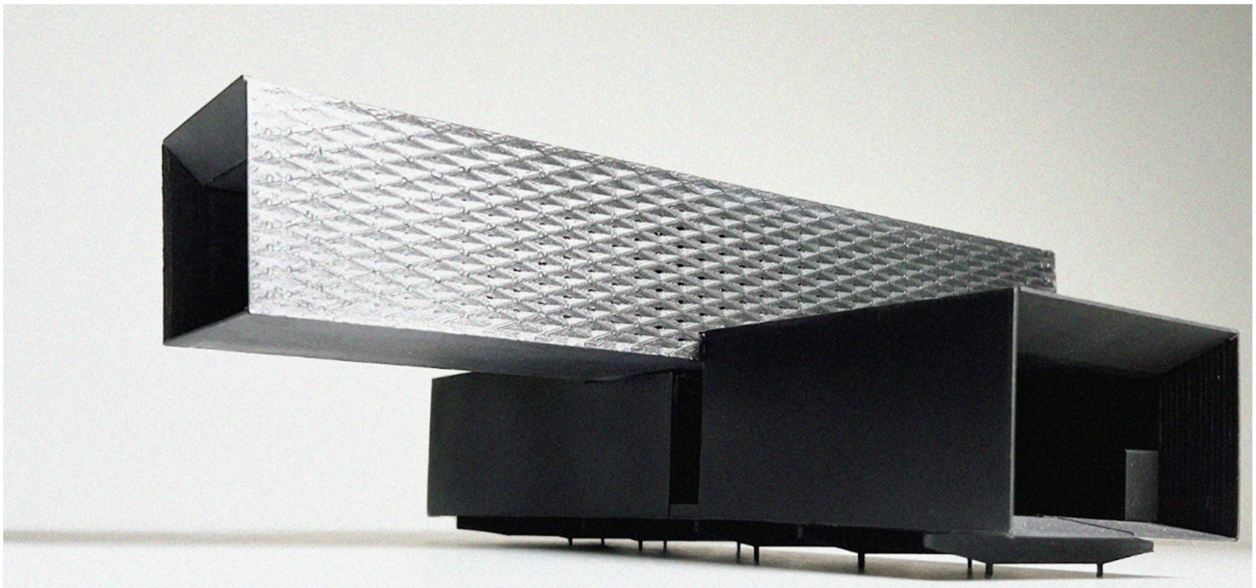


Figure 1. Fulcrum House scale model

In the last decades, the accessibility to digital fabrication technologies positioned composites as an affordable, structurally efficient and low-maintenance alternative to traditional mineral-based and high-energy materials. Of special interest are carbon nanotubes (CNT) and carbon foam (CFoam) from methane and coal pyrolysis respectively, as an environmentally friendly substitute to glass and carbon fiber. This paper presents the design of a principled single-family house, as a first case study to identify the constraints of such a material system, including technology gap, techno-economic and life cycle assessment, as well as building code requirements. In turn, the investigation proposes a suitable design-to-fabrication workflow, which potentially could bring CNT and CFoam materials to the construction of buildings.

Context: To situate the new work, use this section to communicate knowledge of relevant past literature, practice framework, or design approaches within the field. Literature review references and precedents should point to original contributions and not necessarily be limited to the field of architecture. If the focus of the paper involves multiple disciplines, appropriately contextualize your work within each field. Methodological approaches may also need to be addressed.

Composites Vehicles

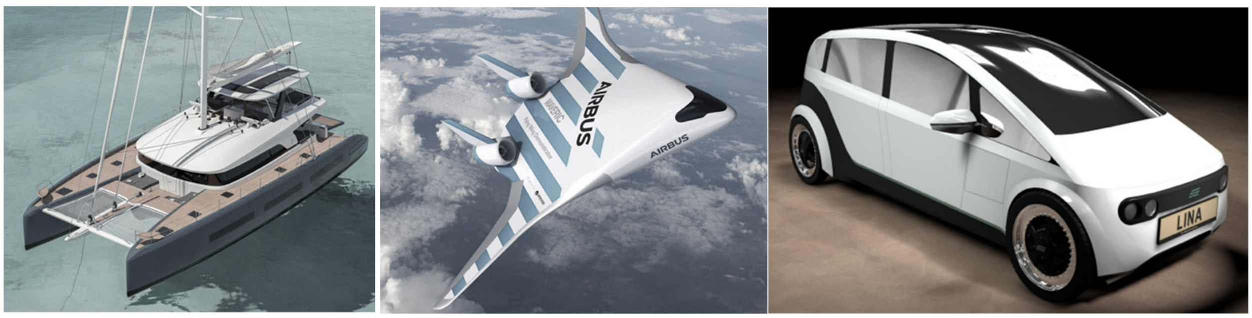


Figure 2. Eco-friendly catamaran built from recycled and biobased composites (Windelo 2021), zero-emission aircraft built from recycled carbon fiber (Meng et. all 2020, 1), bio-composite produced car (TU Ecomotive, 2022)

Composite polymeric materials, often referred to as composites, are materials that are extensible used in the prefabrication of complex integrated designs, mainly vehicles, due to their high strength-to-weight ratio and durability. In the shipbuilding industry they are often employed for the prefabrication of single-part elements, such as superstructures, decks, bulkheads, advanced mast systems, propellers, propulsion shafts, rudders, pipes, pumps, valves and machinery. The main reason being that such integrated parts can be materialized without the need of complex joinery, which could lead to potential filtrations, as well as the acquisition of maintenance costs (Neser 2017).

In the aeronautical and automotive industries composites have been incrementally developed mostly into connected sandwich panels, which is currently one of the most popular composite systems (Castanie et. all 2020) While these multilayer configurations present a unique opportunity for the “hyper-choice of materials and architectures”, they are still mostly relegated to specific parts of the vehicle (Mouritz 2001). This limitation is rooted on the complexity of the manufacturing process required to build bespoke panels; however, several companies have already automated specific parts of their production lines (Jacob 2010) (Mills 2001).

Composite Architecture

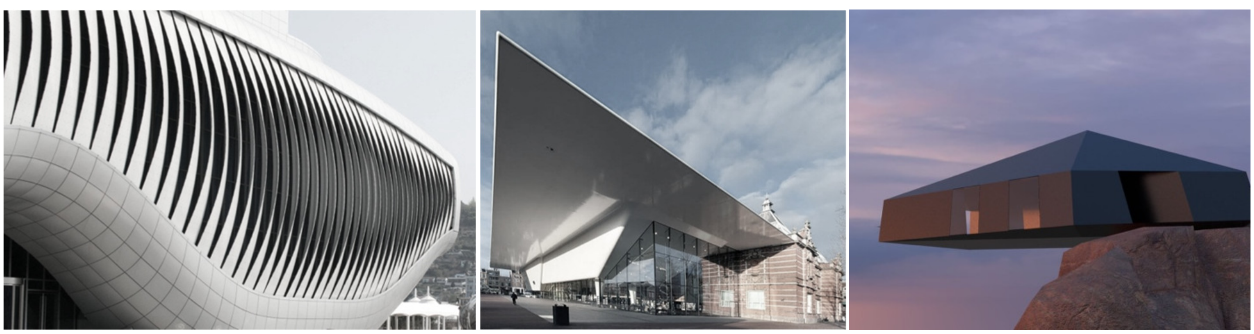


Figure 3. glass fiber façade of the One Ocean Thematic Pavilion (Technology in Architecture, 2023), carbon fiber integrated roof-façade of the Stedelijk Museum (Holland Composites 2001), carbon fiber panels of the Stealth House

Besides for reinforcing traditional construction techniques (Makar 2003) composites have been used for the construction of free-standing structures, such as free-form facades (See fig. 3, left) and parts of buildings (See fig. 3, middle). These architectural elements are often build from glass fiber, which is one of the more economical composite solutions or carbon fiber that introduces a high strength to weight ratio. Latest research (See fig. 3, right) (ICD 2019) have been pursuing the development of glass or carbon fiber systems that are produced through entirely automated fabrication processes and that aim at exploiting the structural potential.

Methodology:

The investigation is conducted through a specific case study, titled the Fulcrum House, which is comparable to a single-family standard house of 2400 sq ft. It contains two volumes assembled on-site from eighteen transportable panels that result in a structurally challenging cantilever. The program consists of a shared living room (See fig. 4, 2), kitchen (See fig. 4, 3), dining room (See fig. 4, 4) and restroom (See fig. 4, 5) included in the bottom volume and two suite-apartments (See fig. 4, 6 and 9) with their corresponding bathroom (See fig. 4, 7 and 8) and terrace (See fig. 4, 10 and 11), as part of the top volume.

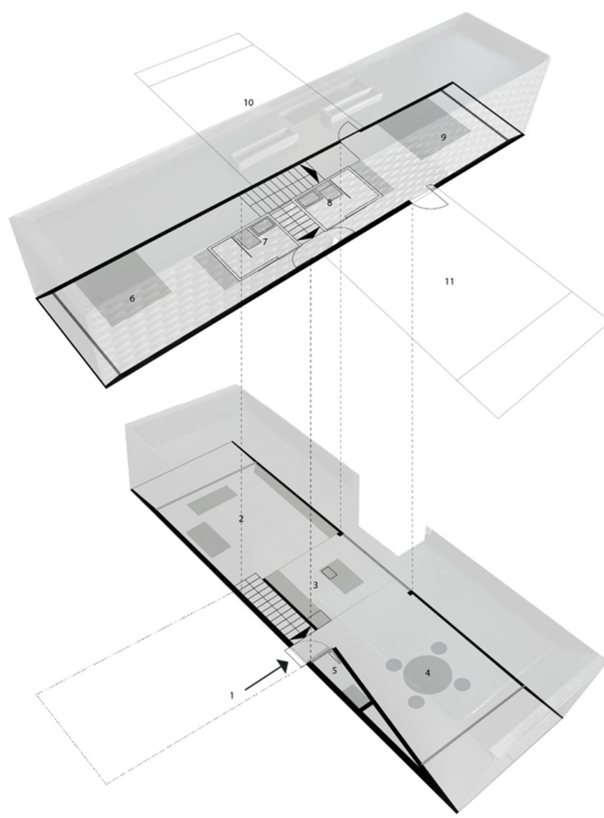


Figure 4. Fulcrum House axonometric and program

While designing the Fulcrum House we identified the involved design parameters and constraints, which are related to the material system and its fabrication process. This required the conduction of several studies, including 1. technology gap assessment, 2 techno-economic and life-cycle assessment, and 3. building-code gap. The following section serves to introduce the conducted studies and describes how the findings informed the final design.

Technology gap assessment

The study defines a structural concept for the Fulcrum House to assess its structural capabilities. It consists of a core at the intersection of both volumes (staircase) that allows transferring loads from the cantilevering volume towards the bottom and ends in a series of eccentric pilings (See fig. 5). From top to ground, It integrates tension and compression composite struts (See fig. 5, purple) which transfer loads vertically towards the beams that support the house (See fig. 5, green) and finally to pilings, which allow guiding loads to the ground. Internal walls (See fig. 5, red) allow counteracting lateral forces, which are complemented by integrated stiffeners that bridge the struts and walls.

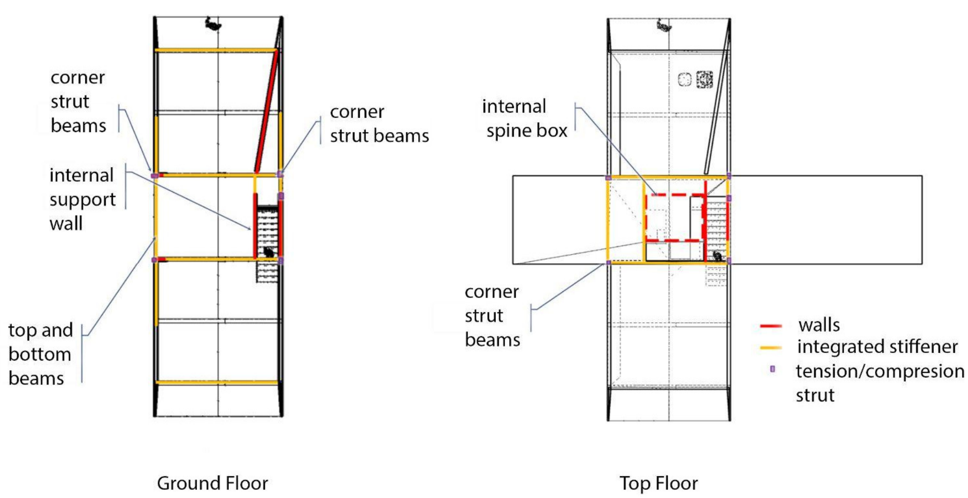


Figure 5. Fulcrum House Structural Concept

The study proposes a suitable sandwich panel arrangement that considers structural, acoustical, thermal and fire retardancy performance. It consists of a compound core of EPS and CFOAM and two external CNT structural skins that are bonded through CNT tubular skins filled with resin (See fig. 6). In addition to this configuration, the study defines laminates for each building component (e.g. floor, walls, roof, parapets, etc.), which allow quantifying materials for the entire design.

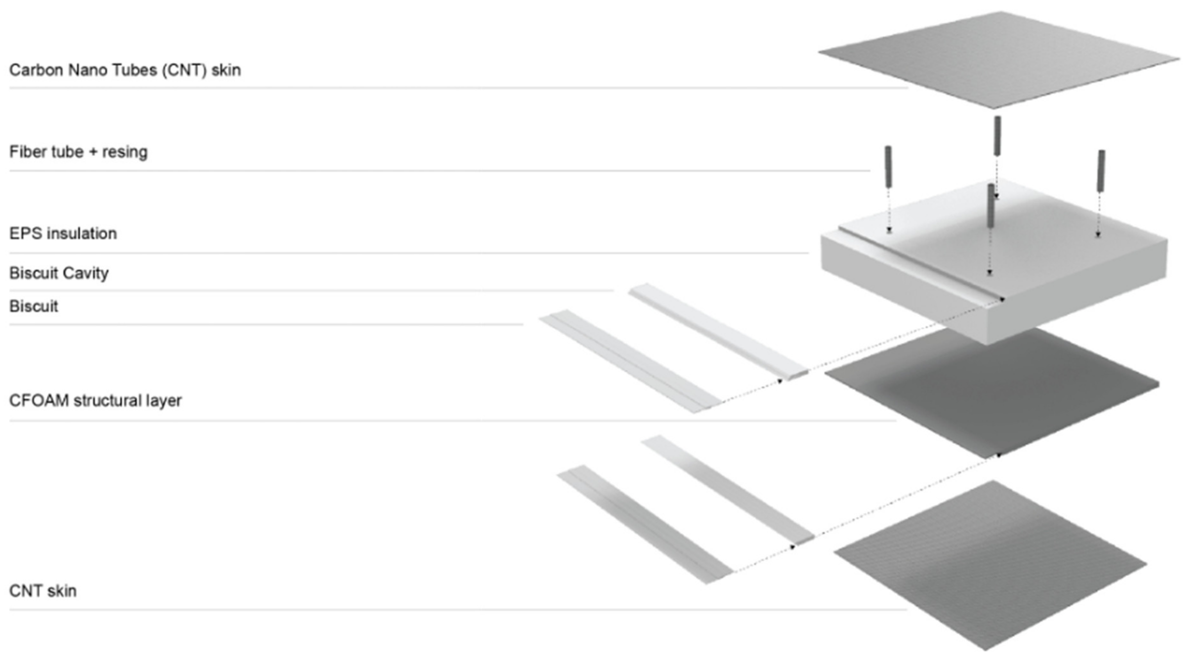


Figure 6. Optimal sandwich panel arrangement

The properties of CNT and CFOAM were quantified through testing performed by research partners, including for example densities, young modulus, stiffness, weights. However, the scope of the investigation and the lack of data regarding CNT led to the conduction of several complementary tests. Additional, structural testing for sandwich panel arrangements were required, as well as benchmarking tests (See fig. 7).

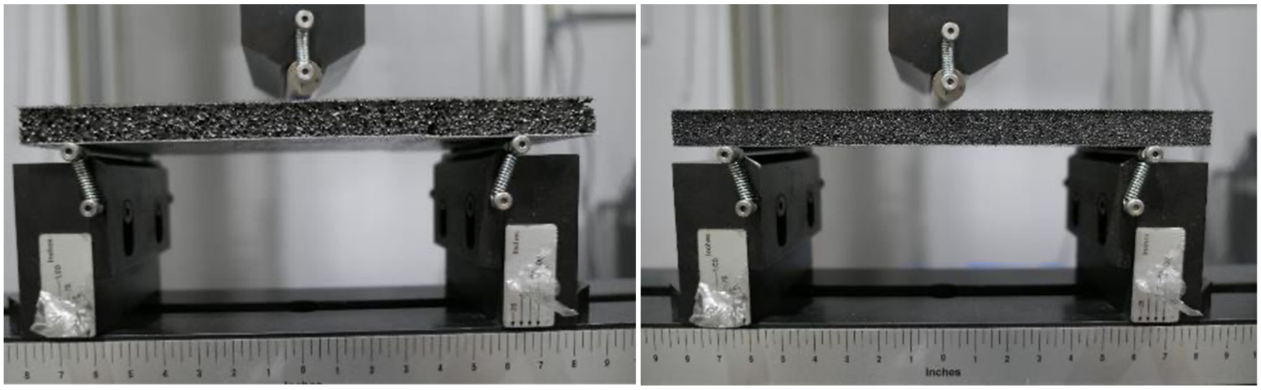


Figure 7. Tests performed on specimens of CFoam 20 (left) and 30 (right) with CNT laminates

An FE model was constructed, which served to analyze the structural capacity of the proposed design and to benchmark it with the same design but with glass or carbon fiber skins and PET cores (See fig. 8, left). It was built using layer shell elements, which is considered a valid method for multilayer elements and simplified free edges and complex details (e.g. joints, integrated supports, etc.). The performed analysis include: deformation (See fig. 8, right), reaction forces, in-plane internal shear, in-plane forces, internal moments and reserve factors.

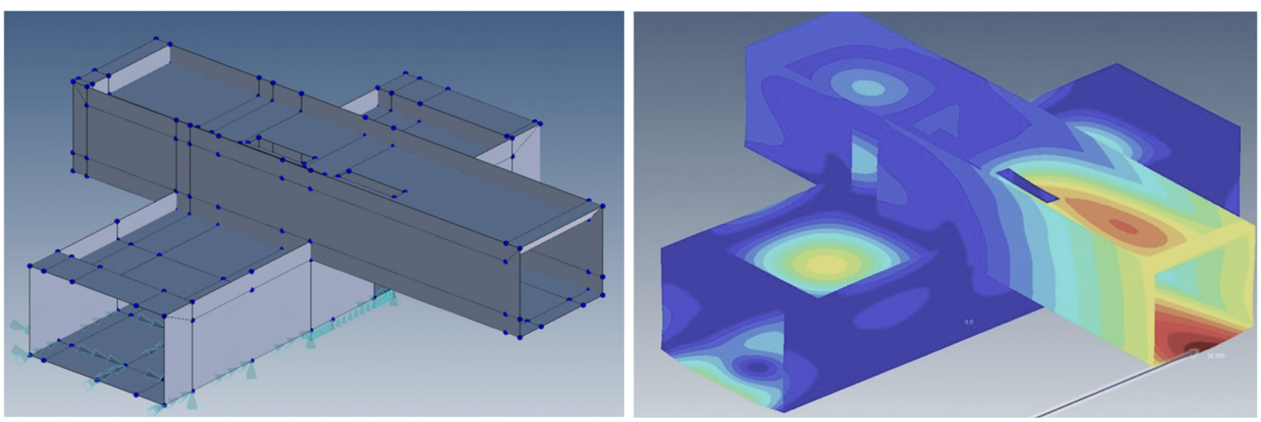


Figure 8. Fulcrum House FE model (left) and its deformation analysis as example of the performed test (right)

Techno-economic and life-cycle assessment

In order to quantify costs and perform life-cycle assessment, material and processing quantities were calculated. This considered the proposed panel sandwich arrangement, the bill of material (BoM) and connection types. The machining toolpaths and manipulation processes were simulated and quantified for two working shifts of eight hours per day. The panels were built from smaller boards nested into 4.8x19.5m motherboards.

	FEM Weight (Kg)	Weight BoM (Kg)	Weight per Area (kg/m2)	House Cost ($)	House Cost per Area ($/m2)	Core Cost ($)	Skin Cost ($)
Glass fiber	12635	14733	47.5	57424	185	34358	23066
Carbon fiber	15000	16838	54.3	88314	285	4342	83971
CNT	15369	17257	55.7	23825	77	4342	19483

Table 1 Cost estimation for the proposed design built from Glass fiber, Carbon fiber and CNT

In addition to TEA, the study performed LCA by following guidelines of ISO standards (ISO, 2006a, 2006b), which propose three stages: life cycle inventories, impact assessment and analysis-interpretation. The scope of the study was cradle-to-grave and used as baseline scenario the 4C climate zone as established by the International Energy Conservation Code (IECC). Moreover, the Building Attribute to Impact Algorithm (BAIA) was used for benchmarking, as well as existing literature.

The life cycle inventory gathered inputs for each element of the system, including: raw material extraction and building material refinement, transportation of refined material, fabrication into ready-to-assemble modules, transportation of modules to site, house construction, house use-phase, and demolition. The model uses existing Ecoinvent dataset for pulverizing lignite coal and adapted it for using hard coal. It is estimated that approximately 29% of the pulverized coal input is lost through organic compounds. The organic fraction is then oxidized (burned) to prevent harmful respiratory impacts. In addition to the off gassing, 24MJ of on-site electricity energy is used for a 1kg of C CFOAM material.

The energy use at the fabrication stage was calculated from the total toolpath as predicted in the CAD model design of the Fulcrum House. The milling speed is assumed to be 100 IPM, or inches per minute. Therefore, the two factor allows for calculating the total equipment run time. Power consumption is assumed to be 1kW. Multiplying the power consumption with the calculated run time in hours allows for estimating the fabrication energy consumption in kWh.

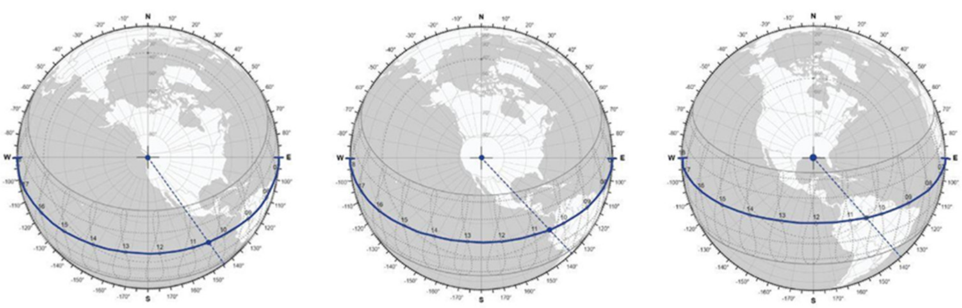
Energy consumption of the construction phase was based on a study by Quale et al (2012) for an average 2,000 ft2 home in the US. The study surveyed numerous construction firms specializing in assembling modular homes as well as standard stick-build home builders. The survey detailed material consumption for the modules, transportation of the materials, worker transport, energy use at fabricator and on-site, and waste generated. In this study only the worker transport and energy use at the construction site were incorporated, as CFOAM specific data have been obtained for the other data points. Specifically, the study distinguishes energy use "on-site" and "off-site". Off-site is the module fabrication step, so energy uses labeled "off-site" are also excluded. Also, data for stick-built homes are omitted as they are not relevant to this study.

The use-phase energy calculations are based on the 2017 ASHRA report on energy use intensities (EUI) of existing buildings. The annual energy use values are multiplied linearly by 2,400 ft2 (223 m2) and by 50 years of building lifetime for this study. Therefore, the electricity and fossil fuel use for 50-year life single-family homes in zone 4C are 4,327,000MJ and 535,200MJ, respectively.

The environmental impact categories were selected from the ReCiPe method for LCIA. ReCiPe has a comprehensive scope of impact categories.

Three published LCA studies were selected as a benchmarking exercise to gauge whether the Fulcrum House results are within acceptable ranges for energy consumption and Global Warming Potential. The study indicates that the embodied carbon is a smaller contributor than the use phase. This pattern is also echoed in the embodied energy and lifetime energy use. In consequence, the investigation focused on the design parameters that can be adjusted according to the use phase and propose to validate it three climate zones.

Location	Seattle, Washington	Salt Lake City, Utah	New Orleans, Louisiana
Climate Zone	4C	5B	2A



	Lower sun angles at all times of the year	High overhead sun in the summer and lower angles in the winter	High overhead sun in the summer months
Temperature	-5 to 32C	-13 to 38C	-5 to 32C
% of daytime sunshine	46%	70%	60%
Wind	Winter-SSE, Summer- NW	NNW, S	Winter - N, Summer-S
Solar Radiation	1,301kWh/m2 relatively cloudy year - round	1,715 kWh/m2 relatively cloudy year-round	1,776kWh/m2 relatively cloudy all year

Figure 9. Three climate zones selected to validate the in-use energy analysis of the Fulcrum House

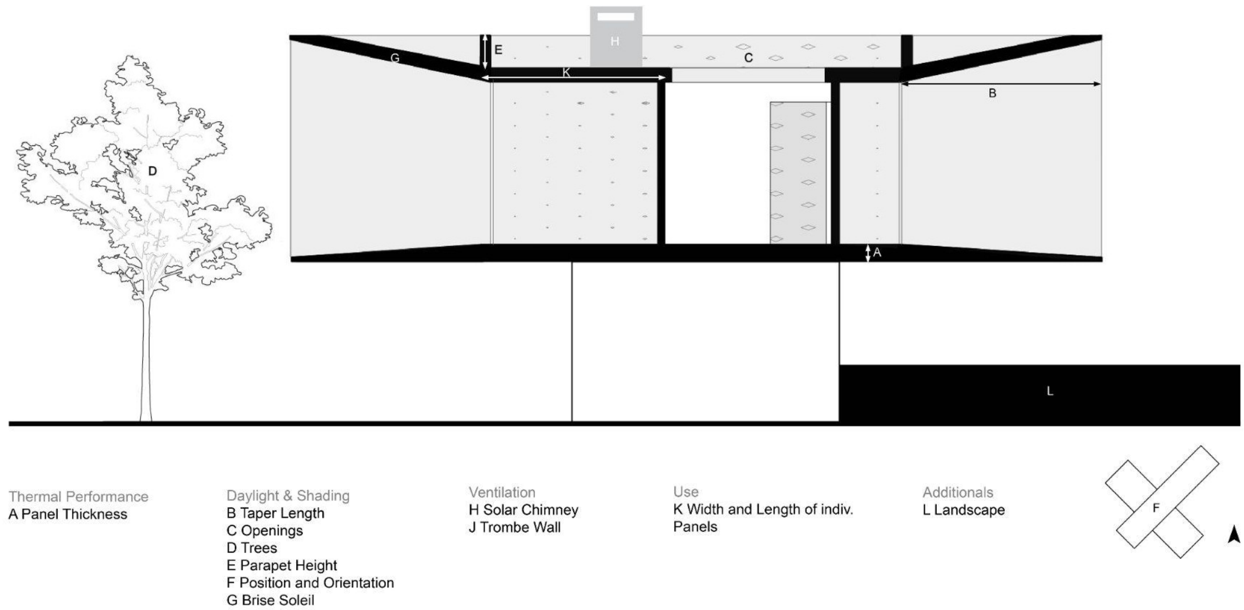


Figure 10. Identified design parameters that can be adjusted to the in-use energy analysis

Case Study I: New Orleans, Louisiana

New Orleans is characterized by hot summers and moderate winters. With warmer night temperatures in the summer and warm daytime in winter as well as high humidity in summer. Some of the strategies of environmental design that have influenced the modifications of the design parameters are enumerated in the following diagram (See fig. 11).

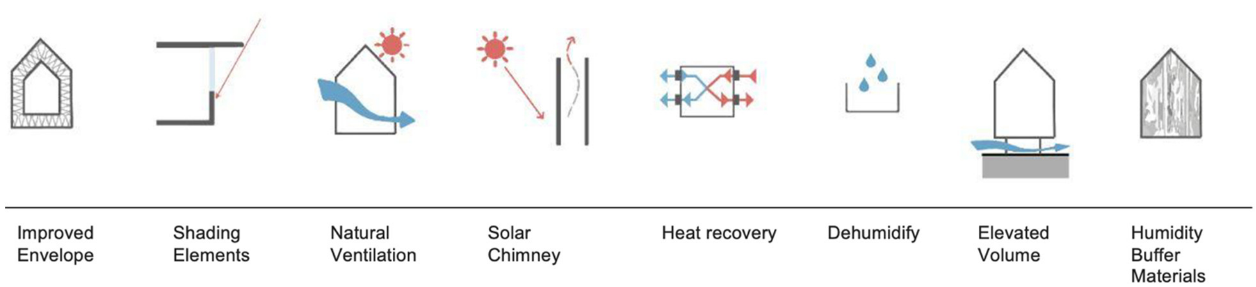


Figure 11 Environmental strategies for the Fulcrum House in the New Orleans Climate Zone

Case Study II: Seattle, Washington

Seattle is characterized by a temperate climate with cool wet winters and drier summers. Some of the strategies of environmental design that have influenced the modifications of the design parameters are enumerated in the following diagram (See fig. 12).

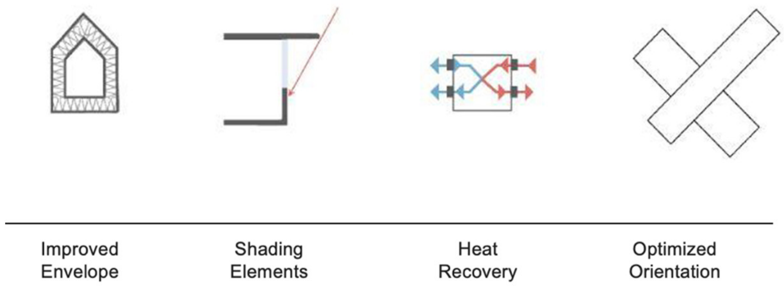


Figure 12. Environmental strategies for the Fulcrum House in the Seattle climate zone

The New Orleans study provided the framework to demonstrate the effect of adjusting the fixed parameter groups on the Fulcrum House and their effect on ASE and sDA. In this section, focus will be on visualizing the impact of Energy Design Principles on reducing the EUI of the house. The most significant change in the in-use energy comes with adopting heat recovery as part of the ventilation system of the house. The final EUI is approximately 35kWh/m2, a 50% reduction from the ASHRAE 2013 baseline of 79kWh/m2.

Case Study III: Salt Lake City, Utah

Salt Lake City is characterized by a hot arid climate with cold winters, hot summers and low humidity year-round. Some of the strategies of environmental design that have influenced the modifications of the design parameters are enumerated in the following diagram (See fig. 13).

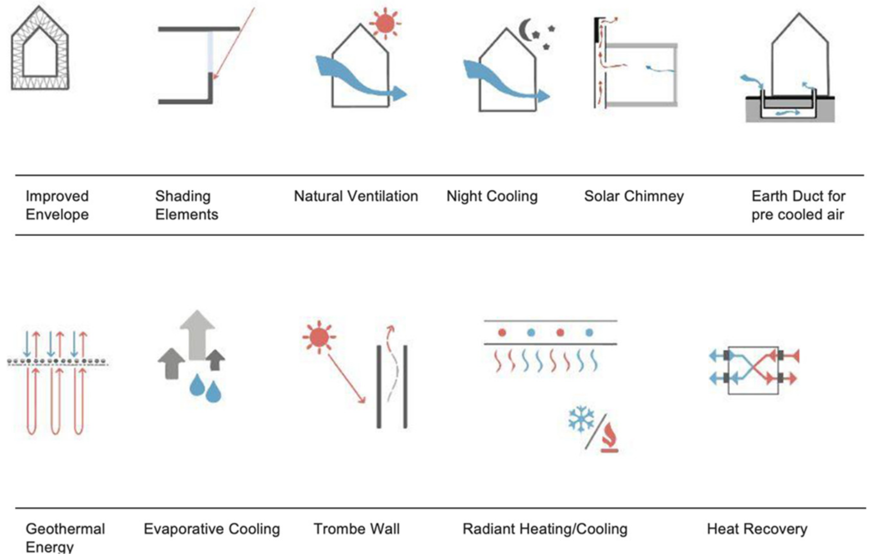


Figure 13. Environmental strategies for the Fulcrum House in the Salt Lake City climate zone

The most significant change in the in-use energy comes with adopting hybrid, buoyancy driven ventilation. The final EUI is approximately 35kWh/m2, a 50% reduction from the ASHRAE 2013 baseline of 79kWh/m2.

Building-code gap and performance metric

The study identifies potential issues of constructing the Fulcrum House in regards of the International Residential Code (IRC 1994). This leads to a revision of standards related to topics such as, wind loads, seismic provisions, snow loads, fire resistance, insulation, light, ventilation, heating, glazing minimums, minimum areas, wall heights, ceiling heights, emergency scape and flood resistance, foundations, floors, walls and roof assemblies, as well as heating, cooling, boilers, water heaters, plumbing, power and lighting.

Design-to-fabrication Workflow

The workflow to design the Fulcrum House starts by exploring parameters, such as the size of the external and internal walls, among others (See Fig. 14, 1). In a next step, the design can be rationalized through a set of feasibility testing techniques, such as assembly sequence planning, detailing and fabrication planning, as well as analysis, such as Finite Elements, Life-cycle and Techno-economic assessment (See Fig. 14, 2). The resulting information is fed back in the design, allowing adjusting accordingly to start again the rationalization procedure. After a set of iterations, the design meets the designer's criteria, resulting into house ready to be fabricated and constructed.

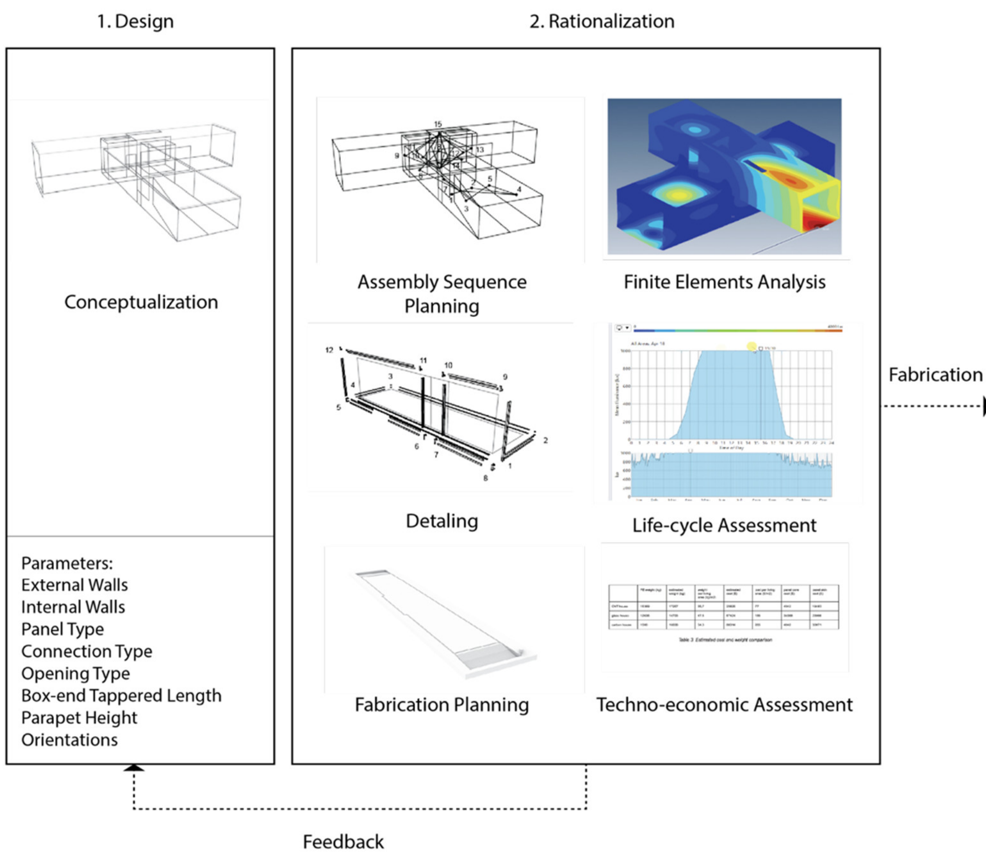


Figure 14. Design-to-fabrication workflow of the Fulcrum House

Results:

The finite elements analysis of the technology gap assessment section presents several conclusions. First, the in-plane forces analysis performed on the CNT design indicates that parts of the structure with high compression forces would require strategically placed reinforcements, which could be implemented for example, by adding more CNT layers. Second, the internal moments analysis points out the need to avoid cuts on edges of the volumes in order to guarantee structural connectivity between roof, wall and floor panels. Finally, the reaction forces suggest that modifying the pilings position or adding a cellar would require a radical change of the structural concept.

The comparison between the three evaluated material systems indicates that deformations on the CNT structure are lower than on the carbon design and significantly higher than the glass one. It also shows that CFOAM performs well as core material and that CNT flocks are not suitable as panel skins, however, CNT unidirectional tapes and sheets perform well and can compete with E-glass. The CNT design proved to be heavier than the glass one (17% more in total) and almost the same as the carbon one. However, projected costs may play a relevant role in favor of CNT. This and the fact that stiffness is the main driving criteria for such housing projects position CNT as a relevant material for the future of construction.

The results of the techno-economic analysis indicates that it takes 1.8 days for the production of one unit, which translates into 2.7 houses a week, 138.8 a year and 331.200 sq ft. realtor space. The estimated costs for producing the Fulcrum House with CNT and CFOAM panels is 2.4 times less than with glass fiber design and 3.7 times than with carbon fiber. Thus, it positions the material system as a economically competitive alternative for the construction of residential projects.

Throughout the LCA study, the work developed a transparent, reusable, extendable model of the life cycle environmental impacts of CNT and CFoam components and buildings. The fact that this model is transparent means we are/were able to identify the drivers of the impacts: which processing steps, which materials, and even design parameters are most responsible for the bulk of the environmental impacts. The fact that it is extensible and is available in a user-friendly environment means that the models can be continually updated and refined, as more data become available via empirical testing and advances in processing technology.

Our LCA analysis showed that, thanks to recent advances in the energy efficiency of key processing steps, the CFoam materials and designs can be competitive with conventional designs from an environmental perspective. Regardless of the source of the energy consumption profile, it does appear that the use phase of the life cycle remains the most impactful stage of the Carbon House. Current results are promising and partially demonstrate the potential of CNT and CFOAM as relevant material within the construction industry. Finally, the three case studies on in-use energy served to identify design parameters and viable solutions that were validated on the three selected climate zones.

In general, the building code study indicated that most of the above introduced topics can be directly translated to CNT composite residential projects. However, seismic provisions, would need the conduction or referencing of laminates properties and in specific cases, new specific ASTM standards should be tested and certified. For example, the design considers the use of unconventional materials, such as a composite foam proposed as roofing weather protection and solar skins. Additionally, panel thicknesses need to be defined according to R-values of the specific climate zone in order to attain a suitable energy performance. While the IRC does not indicate specific acoustic requirements for single-family houses the investigation proposes as solution the use a layer of dumping material within the proposed panel sandwich.

Discussion:

The work identifies design parameters and constraints for building residential projects with CNT and CFoam. This includes considerations regarding the structural implications, environmental impact and building code restrictions, which are iteratively integrated in the design of the Fulcrum House. As such, the work identifies a suitable design-to-fabrication workflow that could eventually developed as a computational design method. Additionally, it could be linked with state-of-the art digital fabrication resulting into a seamless workflow. This would allow for a sustainable alternative to current mineral based high-energy materials and manual inefficient fabrication techniques.

While the introduced study advances the proposed material systems several limitations are identified. The FE modeling approach simplifies the joinery technique and presents several assumptions, as well as further material testing could further improve the obtained results, particularly regarding CNT and new production techniques. A comparative study between the results of the LCA analysis and data from a standard single-family house could extend the proposed cradle-to-gate approach. Finally, the proposed design-to-fabrication workflow could be implemented into a computational tool for allowing designers to negotiate design parameters while considering the enumerated constraints.

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