Light Timber Construction for Affordable, Sustainable Disaster Resilience

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ABSTRACT
Living well in the 21st Century requires resilient architecture. With climate-related disasters increasing daily, architecture must respond by enabling rapid and sustainable adaptability to unforeseeable events. However, current architectural responses can often be merely *adapted* to specific climate hazards rather than *adaptive* to those still to come. Non-adaptive structures are unsustainable and are often priced beyond the means of underserved communities. Can 21st Century architecture be resilient, sustainable, and affordable? Light Timber Construction is proposed as an affirmative answer. This article describes the background, value, methods, and results of the ongoing research project behind this innovative alternative to conventional construction methods. The light-wood framing used in conventional construction may be unsuited for resilient construction, as evidenced by the $24 billion in property damage in North Carolina alone during Hurricane Florence. In disasters like these, the most vulnerable communities often suffer the most, and the Light Timber Construction project aims to create greater equity in resilient housing. This paper describes the innovative, nature-based design strategies and construction methods behind Light Timber Construction as well as its potential benefits in equity, affordability, resilience, and sustainability. Research methods to be discussed include 1) the extensive study of resilient plants and animals in extreme environments, 2) recent full-scale prototype construction experiments, and 3) plans for computer simulation and testing using finite element analysis (FEA). The results of completed research on nature's lessons in resilience will be discussed here, as will the results of recent full-scale prototype construction experiments. The results of upcoming FEA testing will be addressed in forthcoming publications. With nature as our teacher, we are confident that we can adapt our dwellings to our climate crisis so that people of all means can live safely and sustainably in the years ahead.

KEYWORDS: hazard mitigation, disaster resilience, risk reduction

PAPER SESSION TRACK: Coastal Cities: Design Frameworks for Interconnectivity

1. INTRODUCTION

Light Timber Construction (LTC) is proposed as a novel approach to construction hybridizing light wood framing and mass timber construction. It aims to create affordable, resilient, and sustainable structures. Its resilient design applies lessons learned from plants and animals living in some of nature's most extreme environments to architecture. Sustainability in building operation is sought through a design not only adapted to current environmental challenges but also adaptive to the uncertainty of future hazards. Sustainability in the production of materials is sought through the efficient use of renewable, carbon-sequestering wood products. Affordability can be achieved by reducing the number of structural members and by the improved durability of LTC's resilient structure. While LTC may prove applicable to multistory construction, this paper focuses on its application to single-family home construction. A prototype single-family home, nicknamed the Geohome, has been designed, and a section built employing light wood framing. Results from this construction experiment led to the creation of the LTC's light timber "lattice framing" system. These experiments also led to design improvements that will be tested by computer-simulated finite element analysis of a structural model in 2022. Results will enable a comparison of LTC to conventional light wood framing with respect to hurricane-force wind resistance. A cost comparison will also be conducted.

Light Timber Construction aims to improve on the resilience of light wood framing in architecture. In 2018, Hurricane Florence caused $24 billion in property damage in North Carolina. This catastrophic damage was not only the result of a powerful hurricane; it also resulted from building stock not designed to withstand such force. Because many of North Carolina's most vulnerable citizens occupy low-quality housing in areas prone to hurricanes and flooding, they were particularly hard-hit by this disaster (Mohai et al. 2009). What are the prospects for vulnerable communities in a future where larger and more frequent hurricanes are the norm? Building codes will continue to strengthen our housing stock, but they are unlikely to keep pace with future hurricanes and other climate disasters. The $24 billion in property damage done by Hurricane Florence in North Carolina is a clear indication that change is needed to the design of housing. The Light Timber Construction project works backward from the ideal of zero damage to create safe, affordable housing for all by asking, "What would hurricane-proof housing look like?"

To answer this question, the author looked to nature. Studying plants and animals in extreme environments has yielded valuable lessons in resilient design. While natural features, plants, and animals suffer damage in climate disasters, the resilience of nature—especially when compared to the $24 billion in damage to non-resilient property from one storm in one state—is remarkable. Light Timber Construction takes lessons learned from onsite analysis of North Carolina coastal ecosystems and applies them to the design and construction of hurricane-resistant housing. The North Carolina coastal live oak, for example, entwines its roots and branches with others to create a stormproof shield where wildlife takes refuge from hurricanes. This and many other lessons from nature add up to a novel approach to hazard mitigation, one that works with nature rather than against it, much as skilled martial arts practitioners use their opponents' strength against them. Because the project is ongoing, this paper focuses on the design approach, initial findings, and evolving plans for the work. The final results of the work will be discussed in forthcoming publications. Here, the author describes the project work to date in order to present the concept and motivate additional hurricane resilient design work across the broader community.

2. GOALS AND OBJECTIVES

2.1 Light Timber Construction Research Program Goals

The Geohome prototype structure is part of the Light Timber Construction research program. LTC program goals include resilience, sustainability, and affordability. LTC performance relative to these goals will be measured against that of conventional light wood construction.

Resilience

Resilience in the face of increasing climate and natural hazards is an essential feature of 21st Century architecture. Buildings must be not only adapted to current climate and natural hazards but adaptive to unpredictable hazards yet to come. Specifically, Light Timber Construction seeks to take advantage of the flexibility of wood structural members and their connections in a "bend but don't break" response to hazards. The result sought is an elastic structure whose movement transforms some of the energy from climate and natural hazards such as wind, flooding, and earthquakes and disperses it in acceptable deflection of the structural system and transfers that energy to the ground.

The connections between structural members are of particular concern with respect to resilience. Light wood frame buildings consist of many small members such as wood studs and their numerous connections. These connections have been found to be the primary source of structural failure in post-hurricane forensic studies (Pistrika and Jonkman 2010). However, alternatives to wood framing such as concrete and steel are not cost-effective alternatives for most coastal buildings. LTC significantly reduces the number of connections in the structure relative to conventional light wood framing. Resilience is also fostered by the structure's fiber-reinforced cement panel cladding, one of the strongest cladding materials available. The large panels also reduce the number of cracks in the building exterior, thereby reducing opportunities for wind and moisture penetration. Fenestration is also designed to minimize opportunities for wind and moisture penetration. Most of these resilient design strategies were developed from the first-hand study of plant and animal behavior in extreme environments.

Sustainability

A green building destroyed by climate or natural hazards is not sustainable; resilience makes buildings more sustainable. Light Timber Construction uses renewable, carbon-sequestering wood products to create resilient housing. Its innovative lattice framing system is designed to use less wood than conventional construction but be stronger and safer in hurricanes. Its fiber-reinforced cement panel cladding also offers environmental benefits, including improved durability, recyclability, and organic composition (Zabcik 2018). LTC's benefits for sustainable, carbon emission-reducing forestry in the North Carolina timber industry will also be explored.

Affordability

Another goal of the LTC project is to make disaster-resistant housing cost-competitive with market housing. This goal can be achieved by reducing the number of structural members and fasteners as compared to light wood framing. In addition, fiber-reinforced cement panel cladding requires less maintenance than many other cladding systems. The resilience of the LTC structure also contributes to its affordability since durability and longevity reduce maintenance and replacement costs. Affordability is also a cornerstone of social equity grounded in the principles of social justice and environmental justice (see below).

2.2 Geohome Prototype Project Objectives

- Develop a collection of nature-based design lessons for resilient, hurricane-resistant housing design (completed).
- Complete construction experiments in the full-scale construction of a portion of a prototype structure (completed).
- Create a three-dimensional computer model of the Geohome, an LTC prototype structure.
- Conduct a finite element analysis of computer-simulated structural prototype dwelling.
- Synthesize test results and define design improvements for publications and proceedings.
- Apply test results to large-scale funding applications to the National Science Foundation, Federal Emergency Management Agency, Department of Energy, Environmental Protection Agency, Department of Homeland Security, and others for whole-building testing.

3. THEORETICAL FRAMEWORK

The Light Timber Construction project combines nature-based lessons in resilient design with the theoretical underpinnings of systems theory, human ecology, and environmental justice. Systems theory outlines a comprehensive method and cognitive framework for understanding complex systems (Bertalanffy 1969). It emphasizes the role of processes and relationships in understanding, analyzing, and modeling dynamic systems and synthesizing complex systems' environmental, social and economic factors. It adopts an integrated human ecology approach to design to synthesize relevant human behavior, hazard analysis, and environmental design. Odum and Barrett (1984) have applied systems theory to the study of ecology, and their work heavily influences contemporary environmental studies. Human ecology targets the interrelationships between humans and their environment (Steiner 2002). However, a comprehensive systems approach has not been consistently applied to hazard mitigation research. The LTC project is grounded in systems theory and human ecology to help ensure a comprehensive analysis of the social, environmental, and economic conditions at work in the coastal built environment.

Environmental justice--the principle that "all people and communities are entitled to equal protection of environmental and public health laws and regulations"--is a critical concern in the development of the LTC system as well (Bullard 1990). Socially vulnerable households often live in low-quality light wood frame housing that can sustain considerable damage during disasters. They also inhabit areas more prone to disasters. Environmental justice performance criteria are woven into the goals of the LTC project and cross-referenced with other architectural and environmental performance criteria to help ensure that the project addresses the 17 Principles of Environmental Justice outlined by the First National People of Color Environmental Leadership Summit (Delegates 1991).

4. CONSTRUCTION

In Light Timber Construction, "light timber" refers to wood products with sectional areas of more than ten square inches and less than forty square inches. This range of wood products includes "4x4" and "6x6" structural members measuring 90mm by 90mm and 140mm by 140mm (3.5 inches by 3.5 inches and 5.5 inches by 5.5 inches), respectively. Whereas light wood framing relies on smaller framing members (wall studs measuring 5.25 square inches, for example,) running in parallel to frame walls, floors, and roofs, LTC uses a lattice structure and X-bracing (Figure 1). By using fewer, stronger structural members, the LTC system reduces the number of fasteners in the structure. This may increase the strength of the structures, as forensic studies after hurricanes have found that structural failure in hurricane-impacted residential construction is due more to the failure of fasteners than to the failure of structural members (Pistrika and Jonkman 2010). The lattice framing of the LTC system also greatly reduces the number of 90° right-angle connections that can place more stress on structural members and their connections. Instead, it relies on X-bracing with more 135° connections that can transfer loads more smoothly to the ground.

In the Geohome experimental structure, fiber-reinforced cement panels (FRCPs) are set into grooves in the structural members forming the walls. Fiber-reinforced cement panels have proven effective in resisting hurricane-force winds and are durable and sustainable relative to many other cladding products (Energias 2019). Setting FRCPs in grooves in the structural timbers also reduces the reliance on mechanical fasteners that can fail in high winds and flooding. The Geohome experimental structure also includes a standing-seam metal roof, another construction system shown to outperform other roofing systems in high winds and heavy rains (Zabcik 2018).

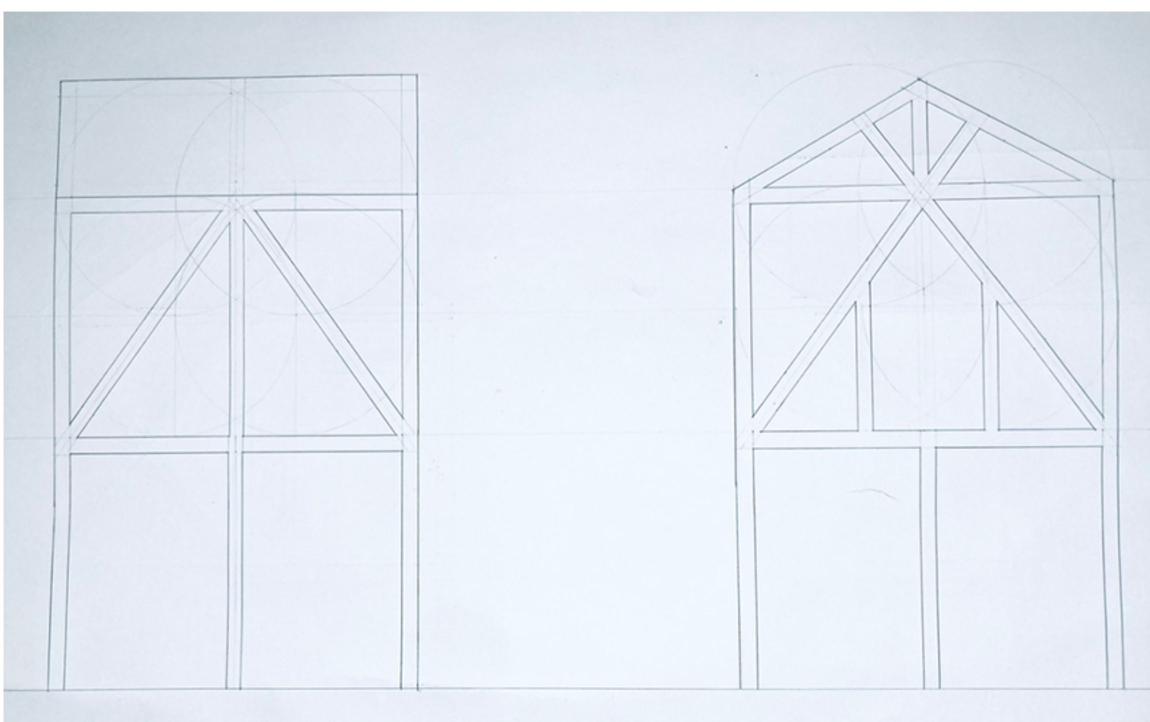

Figure 1: Light Timber Construction uses structural members measuring 3.5 inches by 3.5 inches and 5.5 inches by 5.5 inches in an X-bracing pattern to transfer wind loads to the ground.

5. RESEARCH METHODS

Research methods include 1) the extensive study of resilient plants and animals in coastal Carolina ecosystems, 2) recent full-scale prototype construction experiments, and 3) plans for finite element analysis of a computer-simulated prototype structure. Extensive research was conducted onsite on the Outer Banks and Inner Banks of North Carolina to learn how plants and animals adapt to extreme environments. These nature-based lessons were then applied to the design of an innovative light wood framing system for safer coastal housing. Once a satisfactory design was developed, construction of a prototype structure began at a Raleigh facility. A structural frame was nearly completed when the facility was closed as a precaution due to COVID. Construction did, however, lead to improvements to the frame design, specifically, the replacement of light wood framing with Light Timber Construction.

The project to date has already yielded significant research outcomes. Onsite research on the Outer Banks and Inner Banks has led to an extensive body of data on resilience in nature, which has been applied to the new design and publications and talks by the PI as well as new teaching materials and methods. Lessons learned from field study and prototype construction have also contributed significantly to teaching, as over seventy graduate and undergraduate students have been impacted by improvements to design studio and seminar courses on nature-based resilient design of structures.

5.1 Learning from Nature

The Geohome is a prototype LTC structure, a hurricane-resistant dwelling whose unique design draws from nature. Its wood frame emulates the structure of the coastal live oak; its water-, wind- and fire-resistant cement shell evolved from the study of coastal seagrass; its protective window and door coverings embody the protective features of coastal bobcats, and it perches high on protective stilts like a great blue heron to avoid flood damage. It combines these nature-inspired resilient design features to improve residential building performance in hurricane conditions. A typical strand of coastal Carolina Sea Grass, for example, can be hundreds of times taller than it is wide, and yet it thrives in the face of hurricanes and other extremes. Its form was the inspiration for the compact sectional shape of the Geohome prototype. The interwoven roots and branches of the coastal live oak also inspired the lattice framing of the structure. These and other nature-based resilient design strategies may help the Geohome adapt to nature's forces rather than resist them.

Nature's Principles of Resilient Design

Resilience
Ability to adapt to change. Adaptability.

Regeneration
Renewal, restoration, or replacement of components, relationships, and processes necessary to system health.

Efficiency
Minimal expenditure of energy for maximum achievement of or striving for goals.

Diversity
Wide variety of unique components, relationships, and processes. Diversity of means to achieve goals.

Interdependence
Reliance of components, relationships, and processes on each other for achievement of goals.

Nature-based design and biomimicry are often considered models for resilient design capable of standing up to climate disasters. However, these approaches are seldom based on the direct study of ecosystems. The author has spent over ten years studying extreme environments first-hand, including the world's hottest, wettest, windiest, and snowiest places, and has developed an extensive and detailed collection of design lessons by studying how plants and animals adapt to extreme events and environments. The Light Timber Construction research program then applies nature's lessons to the design of buildings.

Table 1: Resilient plant and animal attributes and their architectural applications.

Plant/Animal	Attribute	Architectural Application	Attribute
Coastal Live Oak	Entwines roots with other live oaks for increased wind and erosion resistance	Root-like foundation	Spreads out to resist hurricane-induced uplift
Seagrass	Hollow, tubular form with remarkable strength to weight and length ratio	Fiber-reinforced cement cladding	Strength

Bobcat	Third eyelid protects eye from dust storms	Pocket storm doors and windows	Protect glazing
Great Blue Heron	Long legs carry body over water	Raised pier foundations	Lift home above floodwaters
Tusk Shell	Tubular structure can withstand water pressure at 2,000 meters	Fiber-reinforced cement board cladding	Withstand hurricane-induced impacts

5.2 Construction Experiments

During the summer of 2020, a full-scale octagonal section of the Geohome prototype dwelling was constructed at a facility in Raleigh, North Carolina (Figure 2). This was the first experiment with lattice framing, but it employed light wood framing members (2x4s) rather than light timber members. The use of light wood framing members required numerous, complex connections and the compound cutting of up to eight structural members for a single connection. In August 2020, the facility was closed as a precaution against COVID, but not before certain conclusions were reached about the design. In order to reduce the number and complexity of connections, it was decided to move forward with a more conventional rectangular section for the dwelling and to employ larger structural members.

Figure 2: Full-scale consrtuction experiments in light wood framing led to the development of Light Timber Construction.

5.3 Finite Element Analysis

Moving forward, the Geohome will be modeled as a three-dimensional computer simulation. Computer simulation of the structure enables the application of scalable numerical methods to calculate mathematical expressions that can, in turn, help the research team predict the behavior of the structure under static and dynamic loading conditions. The dynamic loading conditions produced by hurricane winds can be simulated and applied to the Geohome computer simulation using finite element analysis (FEA) computer software. Finite element analysis uses mathematics to understand and quantify structural behavior (Szabó and Babuška 1991). Using FEA sidesteps the challenges of building a full-scale prototype, outfitting it with sensors, placing it in a hurricane-vulnerable location, waiting for a hurricane to strike, and hoping that the hurricane does not destroy the testing equipment. In this project, FEA will be used to predict how a computer model of the Geohome prototype behaves under computer-simulated wind loads. Data collected in FEA testing will then be compared to standard building framing performance as documented by others to determine if the LTC structure can enhance hazard mitigation without increasing construction costs.

Project Timeline

2019-present Design prototype

2020	Construct prototype structural frame
2021	Refine design based on construction experiments
2022	Create 3D computer model of Geohome
	Conduct finite element analysis of Geohome
	Analyze data and synthesize results
	Document results
2023	Disseminate results

6. PROJECT OUTCOMES AND FUTURE DIRECTIONS

Deliverables resulting from the project will include 1) a compendium of nature's lessons in resilient design (completed), 2) a partial full-scale prototype for hurricane-resistant housing (completed), 3) a 3D computational model of the full Geohome, and 4) test results from finite element analysis. Published results contributing to the body of knowledge on hazard mitigation and resilient design will also be produced. Testing will advance mitigation-related practice by determining the Light Timber Construction system's viability for further development and deployment in socially vulnerable communities most affected by disasters. Data collected from finite element analysis will also help the research team refine the design, possibly leading to the testing of a full-size, residential-scale building against the forces of wind, fire, and earthquakes. Such resilient structures could then play a role in improving building codes for a safer built environment and significantly reduced property damage. With nature as our teacher, we are confident that we can adapt our dwellings to our climate so that people of all means can live safely and securely in North Carolina and beyond.

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