INTERLOCKING CROSS-LAMINATED TIMBER: alternative use of waste wood in design and construction

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ABSTRACT

This paper presents the research and development of an *Interlocking Cross Laminated Timber* (ICLT) prefabricated solid wall and roof panel system. Unlike other solid wood panel systems, however, ICLT utilizes no fasteners and no adhesives. Cross-laminated timber (CLT) for North American markets has historically not been feasible due to relative high cost of fabrication, however, developments in CNC technology and sourcing waste and beetle kill standing dead pine from the intermountain region presents a viable option for creating solid wood technology. With growth projections claiming a 100% increase in building stock before 2030, ICLT is a cost competitive technology for the 3-9 story commercial structures replacing concrete and steel construction, reducing ecological footprint, and increasing indoor air quality of future buildings. This paper presents the research progress of a collaborative team of university researchers and industry partners in developing ICLT for the North American construction market.

KEYWORDS

building systems, material reuse, wood structures, collaborative research, lateral load testing

BACKGROUND

Interlocking Cross Laminated Timber (ICLT) is a prefabricated cross-laminated solid wood wall and roof panel. Similar to Cross-Laminated Timber (CLT) developed in Europe, ICLT is fabricated from 2-7 layers of alternating direction 3” x 6” to 3” x 8” pine stock milled from waste wood. Unlike other solid wood panel systems, however, ICLT utilizes no fasteners and no adhesives, removing the reliance on volatile organic compound (toxic) adhesives, allowing the panel to be disassembled at end of life to be repurposed in the building material supply chain. [Crowther 2009] The exposed wood on the interior provides a thermal mass and humidity regulation factor. Utilizing no fasteners or glues also reduces overall capital cost for either stainless fastener purchase and install or press purchase and set up associated with glue lamination. Conversely, standard mills and timber fabricators looking to diversify their product offering may produce ICLT with existing infrastructure and equipment.

Layering gives the panel strength, allowing low-grade wood to be used in a high value structural condition, estimated to last upwards of 100 years. Compared to the 30-50 year life of most light frame construction, ICLT provides a strong outer structure and enclosure that is durable, meeting the needs of a more sustainable building industry, economically and environmentally. ICLT panels range in size from 6” – 21” in thickness and up to 10’ wide and 25’ in length. (Fig.2) ICLT structures can be built up to nine stories in some cases, efficient in speed of construction, and given the availability of material, potentially affordable for both production home building and large commercial structures. ICLT is currently in the development, testing, and code acceptance research phase in preparation for market acceptance in the next three – five years. (Fig.1)

Figure 1: ICLT sectional profile illustrating a 5-layer system utilizing tongue and groove and dovetail joinery for structural capacity. This ICLT uses standing dead beetle kill pine from the intermountain west forestland.

Precedent

Traditional CLT in Europe is a fully solid product with adjacent layers connected by a structural adhesive. European variations include the use of mechanical fasteners to attach adjacent layers, gaps between adjacent planks in the same layer, and non-orthogonal arrangement of adjacent layers. [Smith 2010] Since the 1990's extensive research has been conducted in Europe to study the properties of CLT panels, including in-plane shear properties [Bogensperger et al 2007, Joebstl et al 2008] out-of-plane flexural and shear rigidity [Gsell et al 2007], bending strength [Steiger and Gülzow 2009], fastening [Uibel and Blass 2006 and Blass and Uibel 2007], and creep in plate bending [Joebstl et al 2007]. In addition to research on material properties, testing of full-scale specimens to evaluate fire [Frangi et al 2008] and seismic [Ceccotti 2008] performance of CLT buildings has also been conducted. In Europe, CLT plate walls, roofs, and floors have exclusively replaced stick framing and many 3-9 story steel and concrete buildings as a mainstream construction method. [Smith 2010] (Fig.2)

Figure 2: Nine story Stathaus Building in London designed by architect Andrew Waugh completed in 2009 is the world's tallest and largest CLT structure.

Research on CLT in North America is relatively new. Since 2005, a series of projects were conducted at the University of British Columbia (UBC) driven by a desire to find a suitable use for low-grade bettle kill pine. UBC's research has focused on developing comprehensive structural computer models to predict the stiffness and vibration properties of various configurations of the CLT products under out-of-plane loading. CLT panel of nominal dimensions of about 4' by 8' were made at UBC to compare two different types of connections, i.e. glue and nails in 2007. Later on, forty pieces of laminated plates of nominal dimensions of 4' by 14' were manufactured to study mechanical performance of CLT products with different layout configurations. A modular structure using CLT was designed and built with locally manufactured CLT structural components in 2009 for display during the 2010 Vancouver Winter Olympics. [FP Innovations 2011]

ICLT System

In order for ICLT to be effective in North America, a client base, resource presence, and design, fabrication and construction capacity must be aligned. Utilizing the integrated collaborative efforts of university research and industry fabrication and construction, a team of researchers has developed the Interlocking Cross-Laminated Timber (ICLT) for wall and roof construction through dovetail and tongue and groove joinery precision cut and assembled using Hundeggar CNC tools. The team is currently conducting a feasibility research project including preliminary structural testing. The ICLT system is showing preliminary signs of success. Two full building constructions are planned between 2011-2013 with modifications and refinements occurring throughout. The goal of this research is to develop a supply chain; product and market for ICLT in the Intermountain West in the next three to five years. (Fig.3)

INDUSTRY DEMAND

Despite the current trend in real estate, building growth in the Intermountain West is projected to double in numbers by the year 2030 [Nelson 2006]. Current practices have depleted our forests and caused environmental degradation. For example, the production of one average sized house (2700 S.F.) in the U.S. consumes up to 9.25 acres or seven football fields of forestland. This is due to planned obsolescence in building design and construction, promoting the continual rebuilding of North American cities and neighborhoods. Estimates of building lifecycle are not encouraging with an average 25 years for short life design, 60 years for mid-life design, and 100 years for long-life design buildings. The age of the building in many respects relates to the function with industrial facilities being short life and civic buildings being planned for 100+ years. [Fernandez 2005]

Not only are buildings planned for obsolescence, they are designed with materials that are not sustainably harvested. ICLT solves the paradox of short life buildings and questionable material sourcing practices. ICLT utilizes two sources of waste wood: construction and demolition waste and standing dead beetle kill pine.

Figure 3: ICLT mockup of corner and roof connections.

C&D Waste

Construction and demolition waste as a result of new construction remnants, retrofit and entire building demolition, constitutes a significant portion of total waste going to our landfills. The U.S. Environmental Protection Agency devotes a sector of their management to construction waste reduction with support for municipalities, research grants, and the Lifecycle Building Challenge to encourage architectural design solutions that encourage lifecycle analysis consideration. [EPA 2011]

For example, the state of Utah produces 940,264 Tons of construction and demolition waste annually. This is equal to 1.88 billion pounds or approximately 853 million Kg of waste each year. Of this mass, 20-30% is attributed to wood waste. [Utah 2008] Based on average feasibility yields, 30% of wood waste is reusable in the form it is currently or being planed for use as a framing member. (Fig.4) In this case the waste wood would be used in an assembly in an ICLT configuration. Based on the average size house in Utah, 2700 S.F., C&D wood contribution to housing units was calculated using both a mass and volume method. Based on mass, C&D wood waste will contribute to producing 1085 ICLT houses per annum. Based on volume, C&D wood waste will contribute to producing 617 ICLT houses annually. For the average amount of C&D waste for every 2700 S.F. house demolished, these numbers indicate that it would take 13 houses in total to be demolished in order to yield enough wood to build one ICLT house. Clearly, C&D waste reuse is not a socially, economically or environmentally sustainable solution for ICLT.

Figure 4: Construction and demolition waste on a job site.

Beetle Kill Pine

Beetle kill pine is abundant in the mountain west. For example, Colorado State University reports that two million acres of national forest in 2008 were subject to pine bark beetle in the state, doubling the number just two years earlier, equating to 44% of Colorado's national forests. This number doubles the amount of standing dead trees since 2006 from 1 million to 2 million acres. [Colorado 2008] Beetle kill is dangerous as it begins decay in the roots creating a hazard of large accumulation of dead wood, which can set the stage for potential high severity wildfires. Alternatively this wood can be used for fuel, directly as chips/ground material or converted to pellets for stoves and boilers releasing CO2 into the atmosphere. However use for energy is the lowest value application of this material and it won't cover the cost of removal and transportation. The preferred use for portions of the trees is higher value products, such as construction for housing and commercial buildings, storing CO2 in built works and then applying the residual to energy use. The Department of Agriculture Forest Products Laboratory places CLT along with small diameter wood as the top two utilization solutions to standing dead pine. Standing dead beetle kill pinewood is low grade and in most cases not adequate for stick frame construction. In a CLT configuration, structural lamination provides ample strength and a positive use of this waste resource.

Forestlands in the intermountain west average 50 trees per acre with an average height of 80' and trunk diameter of 3' at the end of their useful CO2 sequestration life. A mature tree produces 1695 board feet. A forestland of 1 million acres of standing dead beetle kill pinewood yields 85 billion board feet of material. Put into an ICLT configuration of 40,000 B.F. per average sized house (2,700 S.F.) this would produce over 2 million housing units. With an estimated 750,000 units to be added by 2030 in Utah alone, the Colorado standing dead forestland would provide enough material for most of the U.S. intermountain housing demand. (Fig. 5)

Building Market

Although, ICLT may provide a single family housing solution, its greatest economic and environmental conservation potential lies in its ability to compete with North American concrete and steel construction, most notably in mid-rise multi-family and low-rise non-residential construction. Notwithstanding this potential, growth of CLT market share in general will be slow until cost competitive, quality-assured production is readily available and the products and building system are recognized by North American building codes. The market uptake of CLT can be accelerated by coordinated efforts in the research, product standard and codes, and through market promotion. [CWC 2010]

Coordinated support by the research community will be critical to early projects, particularly with code approvals, seismic, fire and connection requirements providing the most significant early challenges. Similarly, coordination of the technical work in support of the US and Canadian product standards and building code recognition can expedite the required approvals longer term. It is estimated that the CLT market will grow 5-15% in the next 5-15 years accounting that for initial investment in product development there will be a 7:1 ROI for the 3-5 year timeframe and a 25:1 ROI for 10+ years out. Europe's market experience with CLT over the last 20 years illustrates that early proprietary systems that prove quality assurance for ANSI and code acceptance are key factors that will determine CLT success long-term. [CWC 2010]

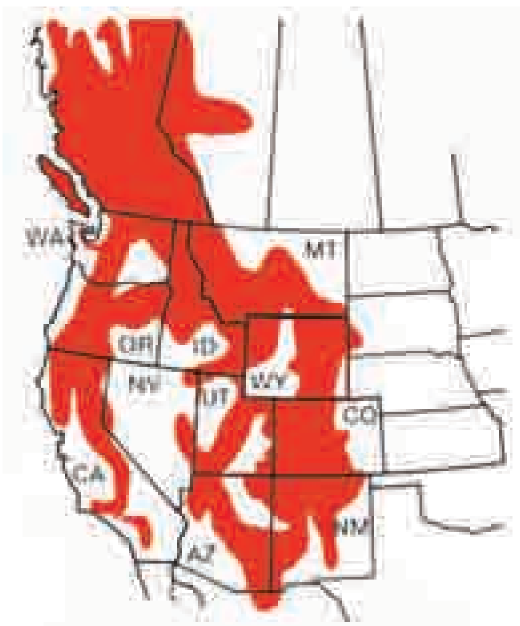

Figure 5: Pinewood areas in intermountain west infested with bark beetle. In Colorado 44% of the national forests have been infected, over 2 million acres.

RESEARCH

At the time of writing this paper research has been completed to determine the in-plane lateral resistance of ICLT. Two tests were performed on 8' x 8' 5 layer (15") ICLT samples. The first test took approximately 20 minutes to perform, and was conducted at a rate of .2 in / min. The first actuator used had a load capacity of 22 kips and a maximum displacement of 20 inches. At the end of the 20-minute cycle, the hydraulic system providing power to the actuator failed at a maximum load of 20430 pounds (90.92 kN) and had displaced 3.86 inches (97.94 mm). The

Figure 6: ICLT in-plane lateral load testing

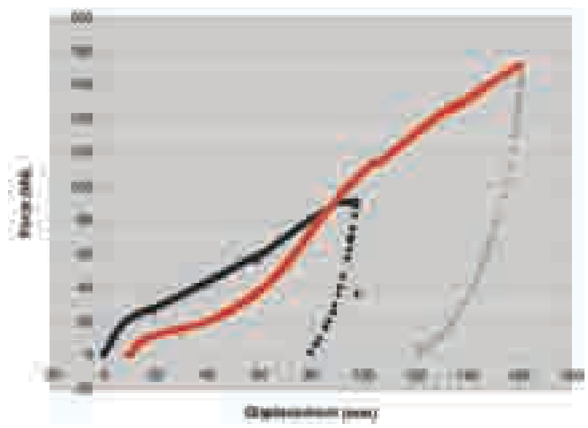

Table 1: ICLT lateral load test results (2)

Shear wall type	P_u (kips)	δ_{ult} (in)
ICLT	38.3	5.97
glued CLT	10	1
Light frame wood	4.5	.89
ICF	34.2	2.66

Table 2: ICLT lateral load results compared to glued laminated CLT, light wood frame and ICF.

second test was performed on the same wall segment as before, only this time with an actuator with higher load capacity of 100 kips and a maximum displacement of 6 inches. The second tests was 30 minutes in cycle, with the actuator travelling a total of 5.97 inches (151.6 mm), reaching its maximum displacement. The load at the end of the test measured 38,296 pounds (170.4 kN). (Fig.6, Tab.1)

The results of the two tests were compared against the test results of glue laminated CLT, light wood frame shear wall, and Insulated Concrete Forms. Glue laminated CLT performs at 44 kN lateral load resistance with a displacement of 1 inch (26 mm). [Popovski 2010] ICLT shows a large elastic range. Its plastic range was not realized, while glue laminated CLT has a sizable plastic range. ICLT has more than three times the lateral strength in the elastic range compared to traditional glue laminated CLT. Compared to light wood frame construction at 4553 pounds of lateral resistance and .89 inches (22 mm) displacement, ICLT offers an order of magnitude greater resistance. Insulated Concrete Form (ICF) reinforced concrete wall construction yields 34,245 pounds of resistance at 2.66 inches (67.5 mm) displacement. [Mehrabi 2000] ICLT is testing at strengths of reinforced concrete and structural steel construction making it a suitable option structurally for 3-9 mid-story residential and commercial. (Tab.2)

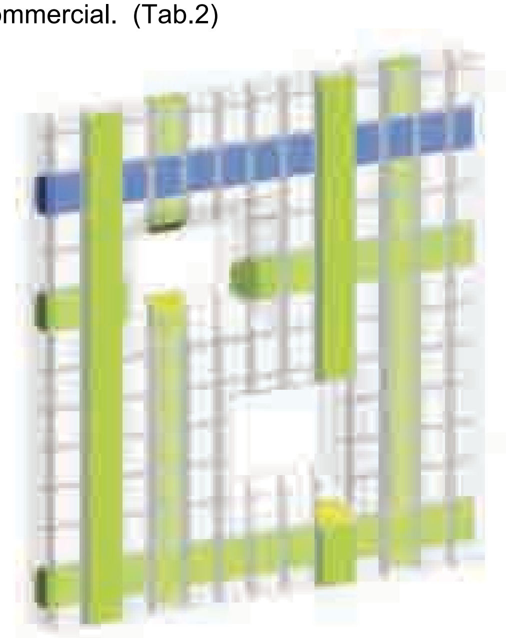

Figure 7: Standard dovetail joint members represented in green. The blue dovetail member indicates addition due to fenestration location.

Additional research conducted to date includes the evaluation of fenestration location versus dovetail locations within a single panel. This was evaluated by 3D modeling the fabrication file in Autodesk Revit to determine the individual board members that make up the ICLT panel. The configuration of the dovetails revealed that for certain locations of fenestration additional dovetail joints were necessary and some boards would have to be mechanically fastened. The team is developing rules based logic for the individual and cumulative dynamic resistance of dovetail joint per wall area. This will aid architecture and engineering designers to be able to make informed schematic design decisions regarding door and window placement. (Fig.7) Panel to panel and corners dovetail connections are also being developed structurally and aesthetically.

Future Research

Although preliminary research suggests success in ICLT, several additional areas of research are needed for wider code acceptance and to adopt this technology to as wide building type applications as possible. The following is an outline of the research plan including intrinsic properties and extrinsic factors that will be quantified:

Technical Testing (3 & 5 layer)

- Structural
  - In Plane (completed)
  - Out of Plane
  - Gravity
  - Joint contribution and software
- Barrier
  - Thermal Mass
  - Effective Resistance
  - Hygrothermal
  - Moisture Control
- Fire
  - Flame Spread
  - Fire Separation

Market Potential (through case studies and quantitative analysis)

- Building Type
  - Size
  - Shape
  - Openings
- Cost
  - Sourcing
  - Manufacturing

  - Initial: economies of scale and means
  - Lifecycle
  - Duration
- Carbon Savings
  - Bettle kill
  - Offsite fabrication
- IEQ
  - Noise Attenuation
  - Air Quality
- Patenting

Code Acceptance

- Research parameters
  - Structural
  - Barrier
  - Fire
- File for code acceptance once testing completed

ACKNOWLEDGEMENTS

ICLT research and development is funded by the U.S. Department of Agriculture Forest Products Lab, BYU Engineering Research Grant the University of Utah Technology Commercialization Grant and the State of Utah Centers of Excellence Commercialization Grant.

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ILLUSTRATION CREDITS

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Figure 2: http://www.structuremag.org (Accessed 01.25.11)

Figure 3: © ITAC

Figure 4: © ITAC

Figure 5: U.S. Department of Agriculture Forest Service, National Disease and Risk Map 2006.

Figure 6: © ITAC

Figure 7: © ITAC

Table 1: © ITAC

Table 2: © ITAC

I CLT interlocking cross laminated timber

Ryan E. Smith, U.Utah (PI)
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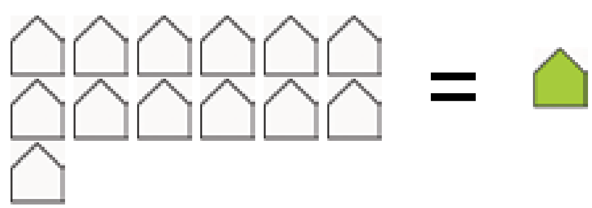
Tom Gorman, Wood Product Lab, U.Idaho
Paul Thorley, Acute Engineering
Kip Apostol, Euclid Timber and Hundegger USA
Department of Agriculture, Forest Products Laboratory

C&D Waste =	940,264 Tons
20-30% yield =	235,066 Tons
Feasibility Rate 30% =	70519.8 Tons
Typical CLT House =	60-70 Tons
# of potential houses =	**1085 Homes**

C&D Waste =	940,264 Tons
20-30% yield =	235,066 Tons
Feasibility Rate 30% =	70519.8 Tons
2700 S.F. House =	6,921 cu ft. wood
Density of wood =	33 lbs / cu ft.
# of potential houses =	**617 Homes**



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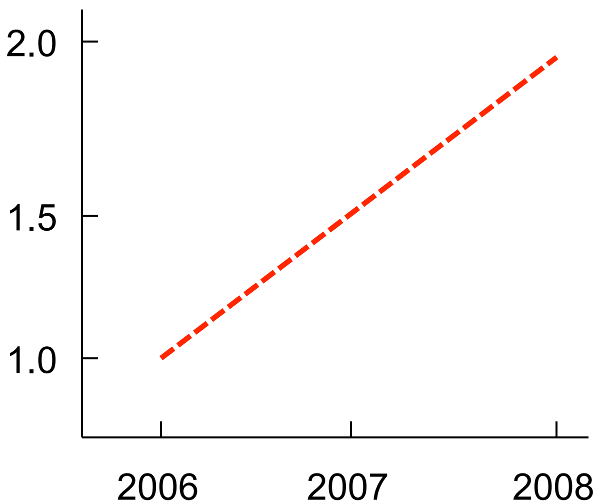
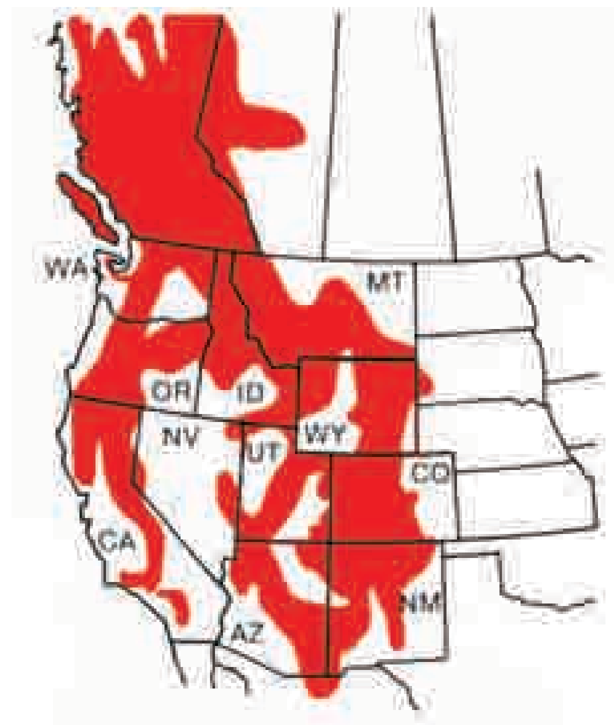
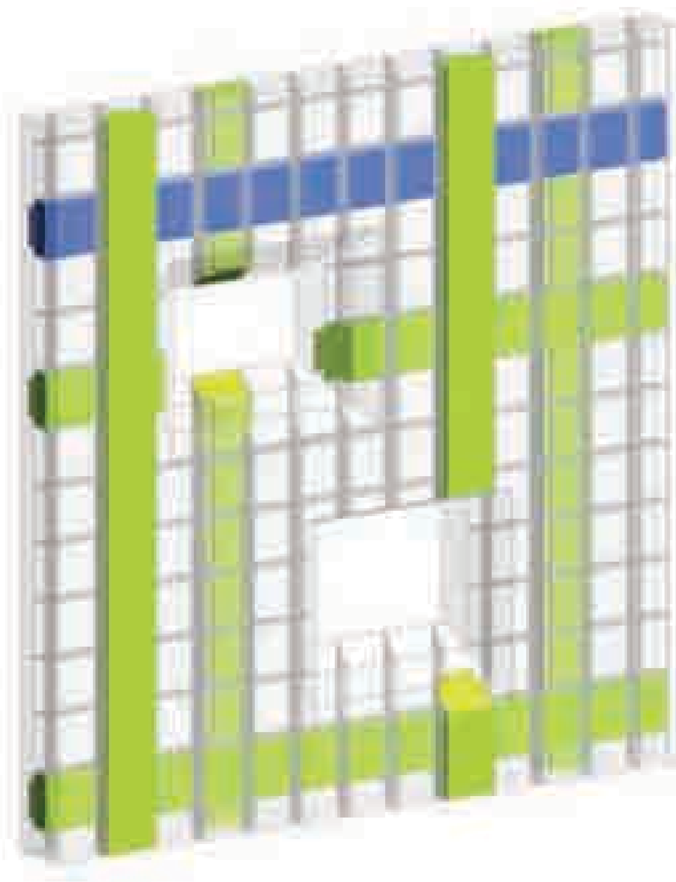
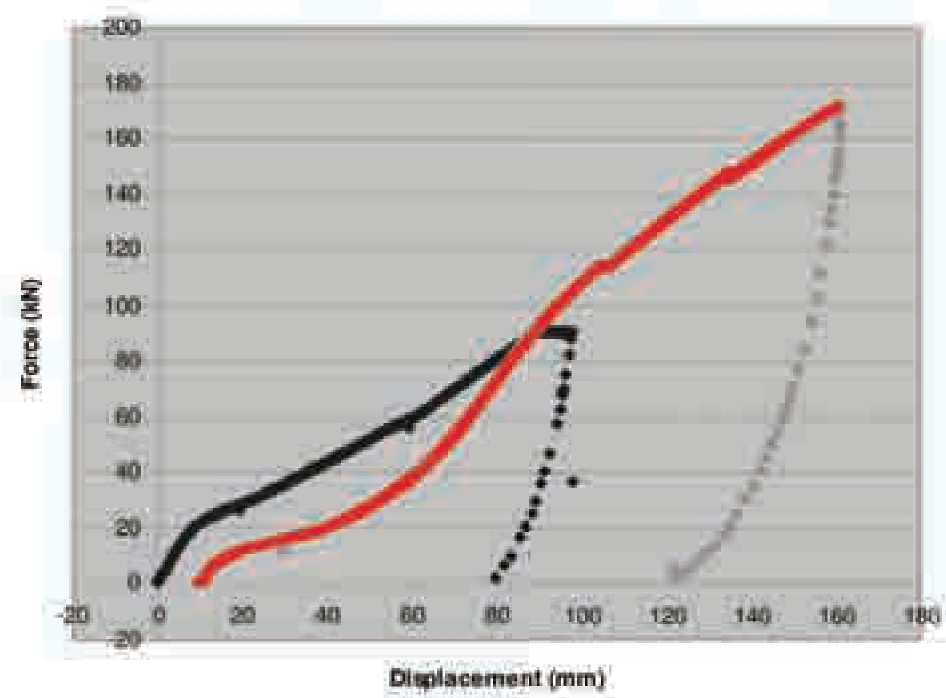


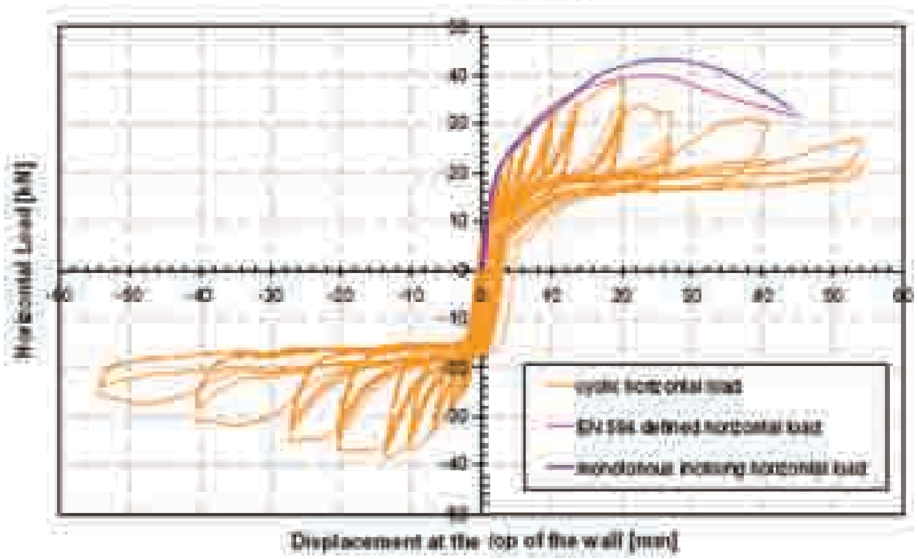


Source: Colorado State University Report No. 5.528

Area =	1,000,000 acres
Trees (50 / acre) =	50,000,000 trees
Board feet =	1695 B.F. / tree
Board feet total =	84,750,000,000 B.F.
B.F. / House =	40,000 B.F.
# of potential houses =	**<u>2,118,750 Homes</u>**







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ICF	34.2	2.66

RESEARCH PLAN:

Technical Testing (3 & 5 layer)

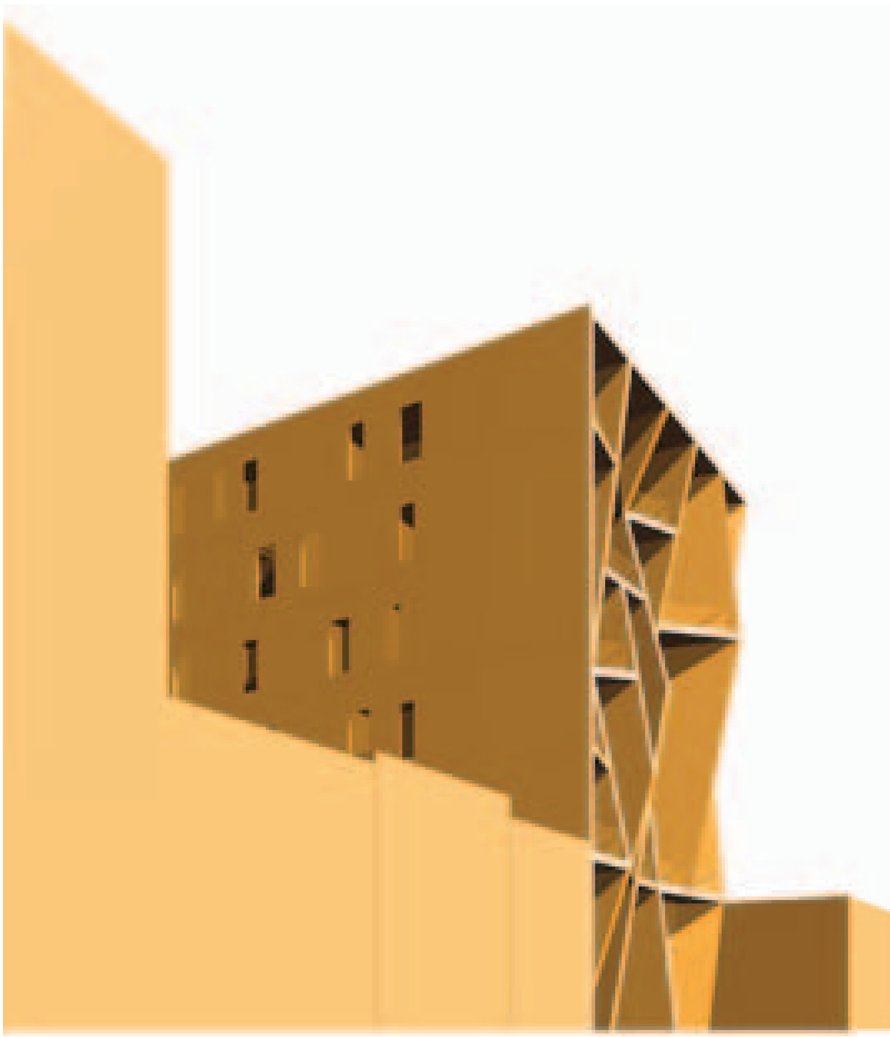
- Structural
- Barrier
- Fire

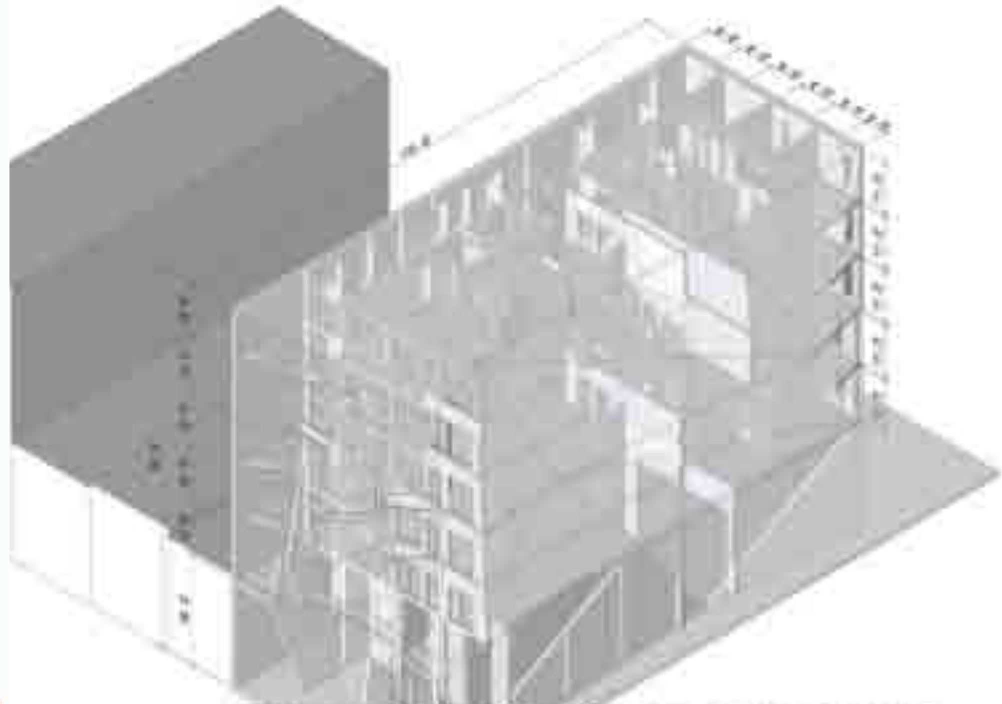
Market Potential

- Building Type
- Cost
- Carbon Savings

Patenting

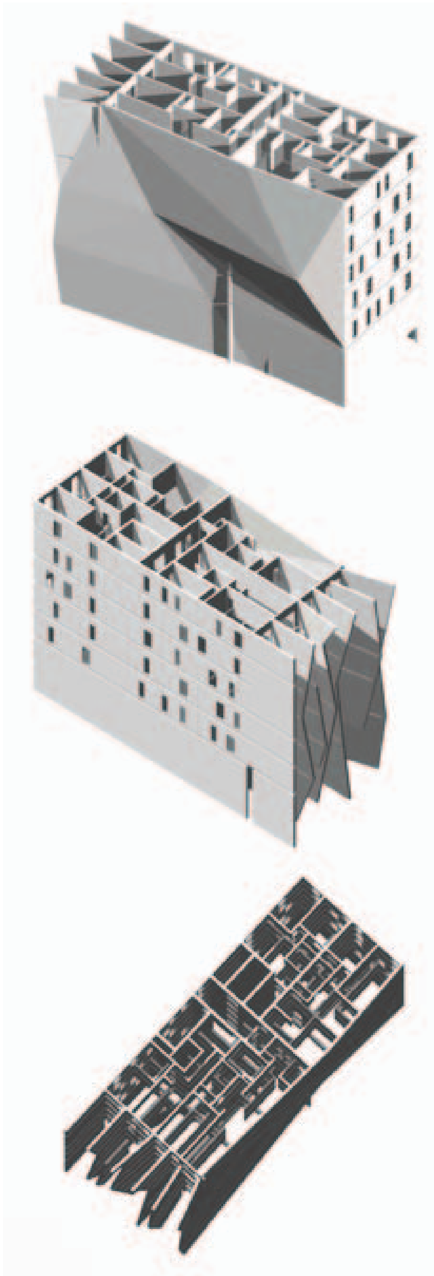
Code Acceptance

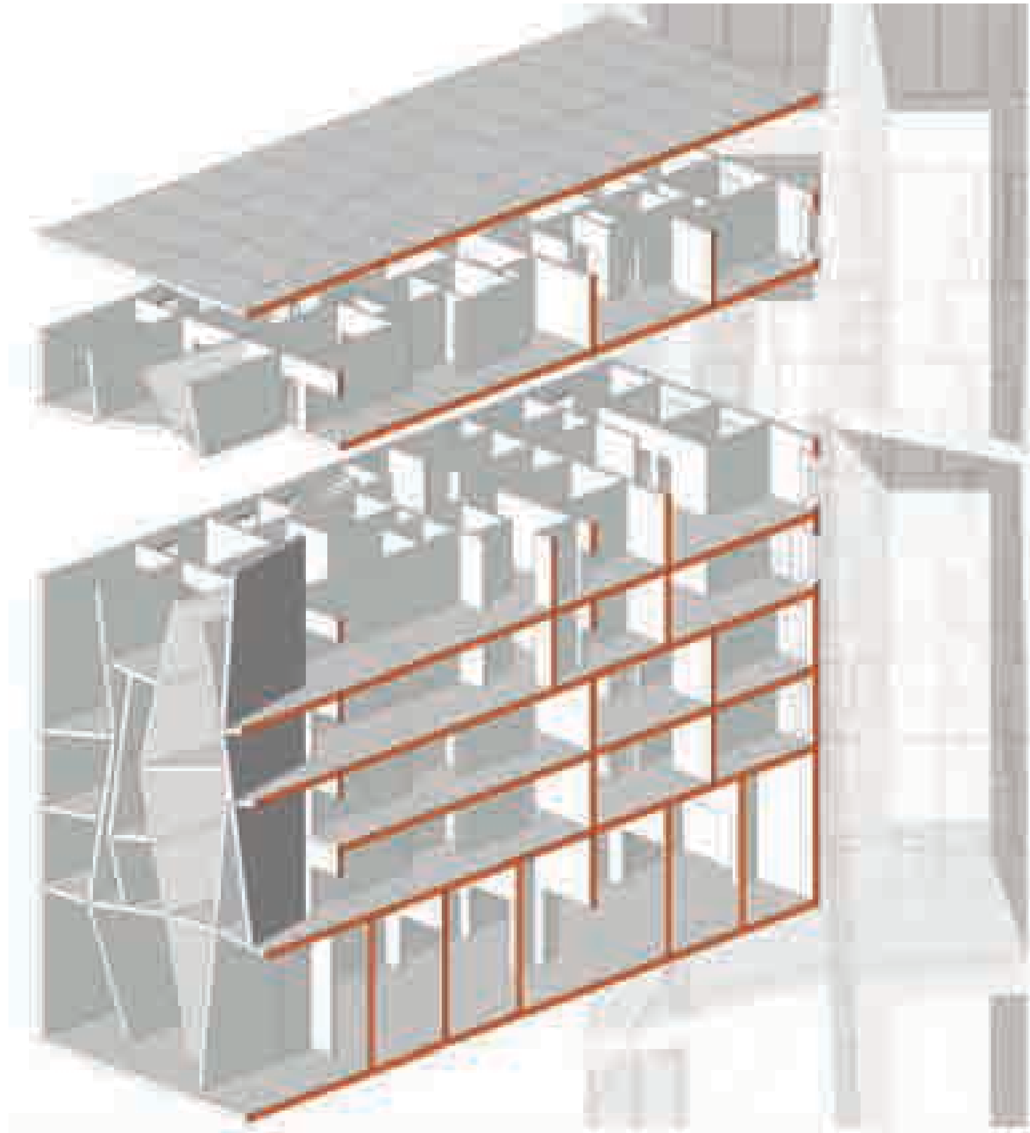


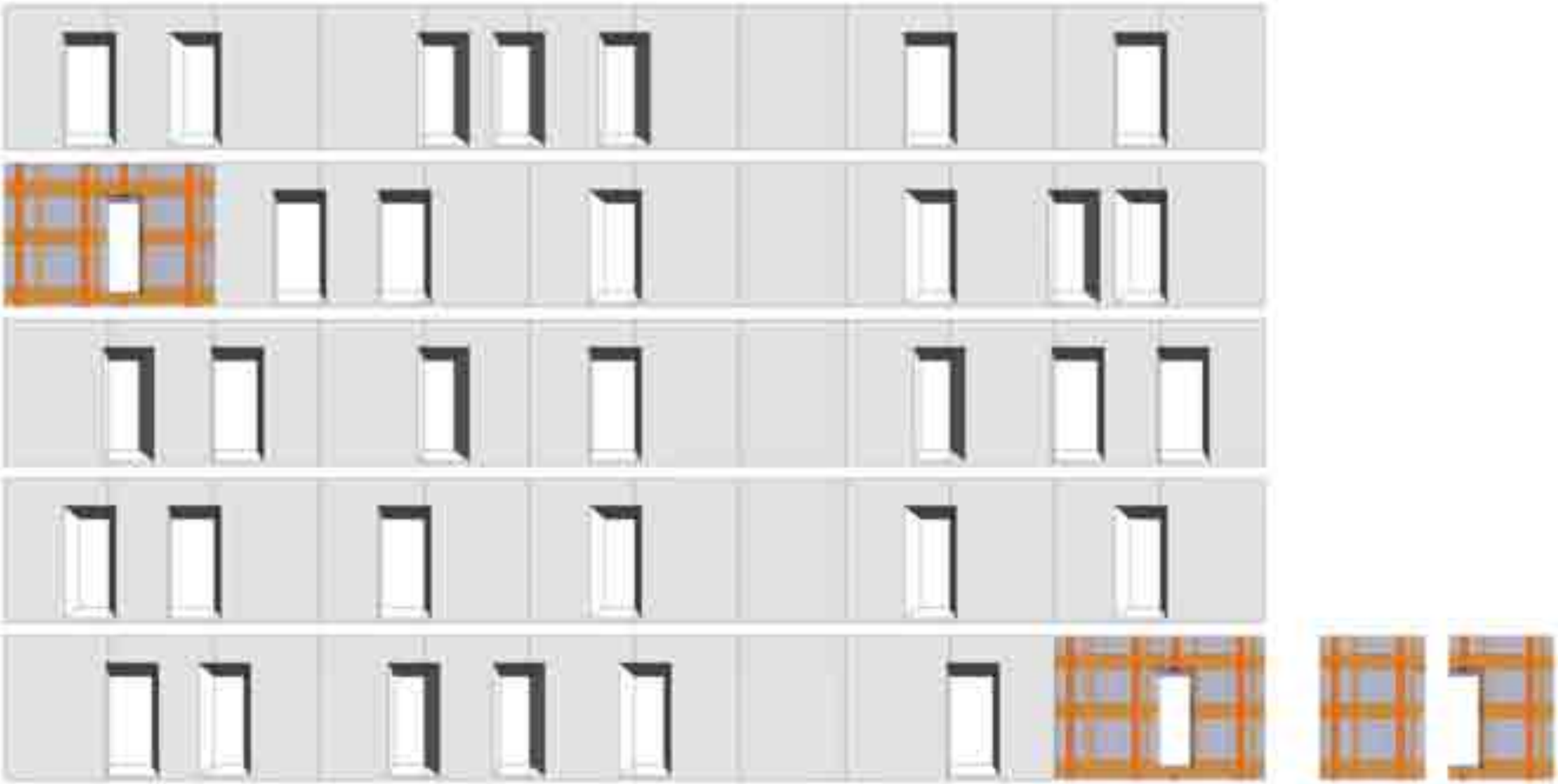


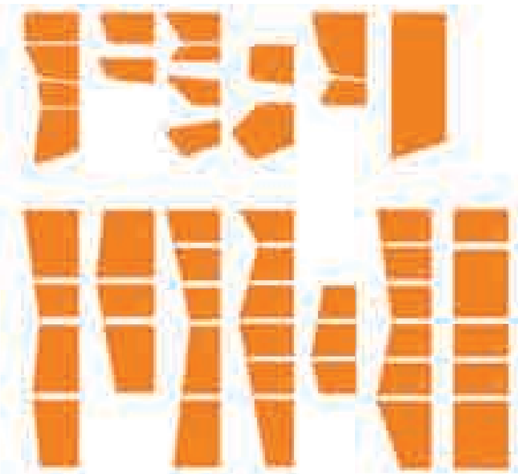
MODULAR GRID - DIMENSIONED PANEL SCHEME

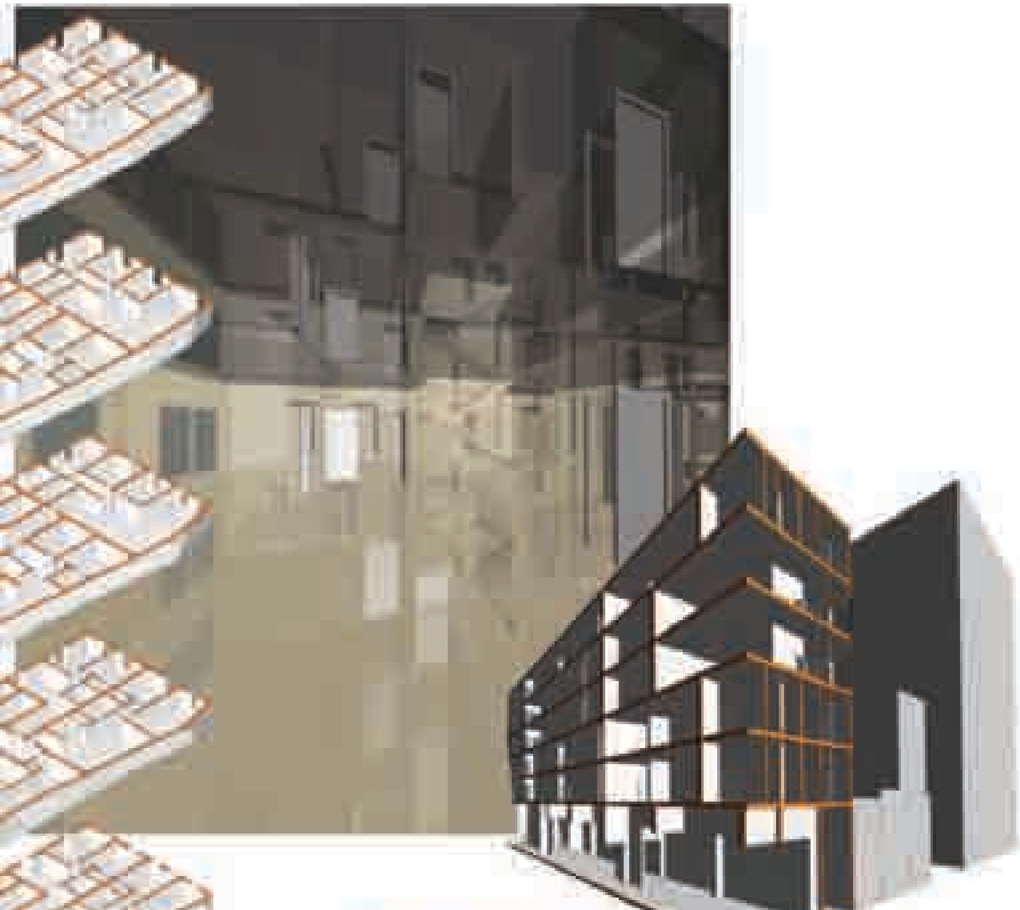
THE PANELIZED SYSTEM IS LAID OUT ON A MODULAR GRID. PANELS ARE DIMENSIONED TO FACE OF STRUCTURE OR ENCLOSURE.



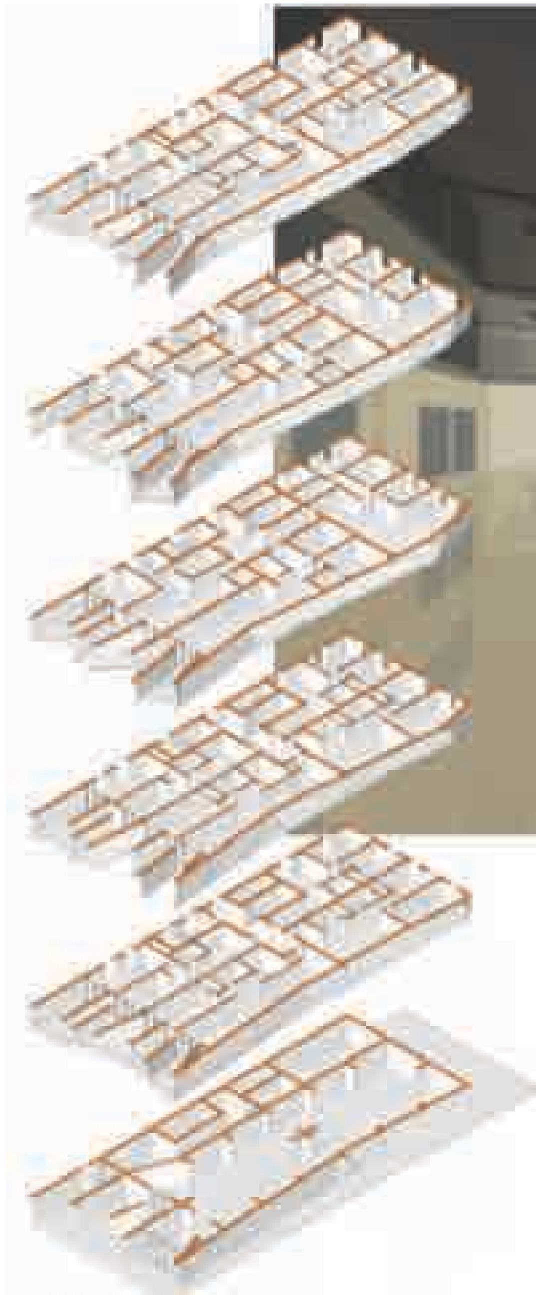








SECTION PERSPECTIVE
(FROM NORTHWEST CORNER LOOKING EAST)



FLOOR PLANS
(CLT GRID STRUCTURE / ALTERNATED PLAN STACKING)