Digital Homes
Seyed Allameh
Northern Kentucky University
Motivation

- 3D printing of buildings allows:
  - Desired Shapes
  - Desired Materials
  - Desired Functionality

- Benefits:
  - Resistant to earthquakes
  - Quick Process
  - Affordable
Desirables in Dream Home

- Affordable
- Functional
- Reliable
- Green

https://www.gardenstateloans.com/3d-printed-homes/
https://all3dp.com/2/3d-printed-house-cost/

Foundation: $277
Walls: $1624
Floor and roof: $2434
Wiring: $242
Windows and doors: $3548
Exterior finishing: $831
Interior finishing (including suspended ceiling): $1170

https://all3dp.com/2/3d-printed-house-cost/
Biomimicking

- Natural Disasters claim lives
- Natural Solution: Mother of Pearl
- Layered Structure
- Self-Assembled

[Source: news.wisc.edu/mother-of-pearls-genesis-identified-in-minerals-transformation/]

[Image: DNA self-assembly, Doyle, Chem. Ox.ac.uk]

[Image: Pearl Causes of Color, webexhibits.org]

[Image: Natural Disasters, natural solution: Mother of Pearl, layered structure, self-assembled]
Digital Manufacturing

- Similar to Printing
- Deposit Material
- Desired location
- Computer Design

https://all3dp.com/2/3d-printed-house-cost/
- 3D printers
- 3D welder
- Contour Crafting

[Links to Autodesk's Redshift 3D printing concrete page]

https://www.autodesk.com/redshift/3d-printing-concrete/
First 2-Story Building in Dubai

https://www.youtube.com/watch?v=69HrqNnrh4
Benefits

- Fast
- Inexpensive
- Mass-Produced
- Reliable
Choices

- Material:
  - Available, affordable
  - Bio degradable, recyclable, ecologically friendly
  - Smart, self-healing, composites

- Design:
  - Strong
  - Lightweight, hollow structures, sandwich structures
  - Durable
  - Resistant against fatigue, creep, oxidation
  - Easily made
  - Quickly made

https://www.pinterest.com/pin/573223858808435420/
https://www.pinterest.com/pin/384987468127253752/
Materials

- Metals
- Polymers
- Ceramics
- Composites
Desired Functionality

- Natural air conditioning
- Green
- Ascetically pleasing
Challenges

- Resistance against earthquakes
- Mainly concrete walls
- Need reinforcement
- Need integrated roof
- Need polymer/composites for insulation
- Innovative Marketing
Benefits: Resistance to Earthquakes

- Integrative Approach to house building
- Elimination of interfaces, joints, weak links
- Use of toughening schemes
  - Resistance against dynamic shear forces typical of earthquakes
  - Resistance against rain, heat
  - Resistance against tilting
- Elimination of 10,000 killed and 400,000 injured in accidents/year


Quick Process

- House printed in China withstands an 8.0-Richter earthquake
- 2500 sf home in 20h


Castel in Minnesota start and completed structures: https://www.pinterest.com/pin/502010689708613086/
https://www.pinterest.com/pin/371969250456613729/
- Rehab costs: 21% Material, 79% labor
- Automation Reduces Labor Cost
- 3D printing improves Designs
  - Reducing mass of materials

<table>
<thead>
<tr>
<th>Portion</th>
<th>Due to</th>
<th>If Automated by CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%-25%</td>
<td>Financing</td>
<td>Short project length and control of time to market will dramatically reduce this cost</td>
</tr>
<tr>
<td>25%-30%</td>
<td>Materials</td>
<td>Will be a wasteless (lean) process</td>
</tr>
<tr>
<td>45%-55%</td>
<td>Labor</td>
<td>Will be significantly reduced</td>
</tr>
</tbody>
</table>

Table 1. Single Family Price and Cost Breakdowns

2011 National Results

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Share of Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Finished Lot Cost (incl. financing)</td>
<td>$67,551</td>
<td>21.7%</td>
</tr>
<tr>
<td>B. Total Construction Cost</td>
<td>$184,125</td>
<td>59.3%</td>
</tr>
<tr>
<td>C. Financing Cost</td>
<td>$6,660</td>
<td>2.1%</td>
</tr>
<tr>
<td>D. Overhead and General Expenses</td>
<td>$16,306</td>
<td>5.2%</td>
</tr>
<tr>
<td>E. Marketing Cost</td>
<td>$4,645</td>
<td>1.5%</td>
</tr>
<tr>
<td>F. Sales Commission</td>
<td>$10,174</td>
<td>3.3%</td>
</tr>
<tr>
<td>G. Profit</td>
<td>$21,148</td>
<td>6.8%</td>
</tr>
<tr>
<td><strong>Total Sales Price</strong></td>
<td>$310,619</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

### Construction Cost Breakdown

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Share of Construction Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Permit Fees</td>
<td>$3,107</td>
<td>1.7%</td>
</tr>
<tr>
<td>Impact Fee</td>
<td>$2,850</td>
<td>1.5%</td>
</tr>
<tr>
<td>Water and Sewer Inspection</td>
<td>$2,952</td>
<td>1.6%</td>
</tr>
<tr>
<td>Excavation, Foundation, and Backfill</td>
<td>$17,034</td>
<td>9.3%</td>
</tr>
<tr>
<td>Steel</td>
<td>$1,012</td>
<td>0.5%</td>
</tr>
<tr>
<td>Framing and Trusses</td>
<td>$24,904</td>
<td>13.5%</td>
</tr>
<tr>
<td>Sheathing</td>
<td>$2,142</td>
<td>1.2%</td>
</tr>
<tr>
<td>Windows</td>
<td>$6,148</td>
<td>3.3%</td>
</tr>
<tr>
<td>Exterior Doors</td>
<td>$2,150</td>
<td>1.2%</td>
</tr>
<tr>
<td>Interior Doors and Hardware</td>
<td>$2,883</td>
<td>1.6%</td>
</tr>
<tr>
<td>Stairs</td>
<td>$1,052</td>
<td>0.6%</td>
</tr>
<tr>
<td>Roof Shingles</td>
<td>$5,256</td>
<td>2.9%</td>
</tr>
<tr>
<td>Siding</td>
<td>$8,739</td>
<td>4.7%</td>
</tr>
<tr>
<td>Gutters and Downspouts</td>
<td>$870</td>
<td>0.5%</td>
</tr>
<tr>
<td>Plumbing</td>
<td>$10,990</td>
<td>6.0%</td>
</tr>
<tr>
<td>Electrical Wiring</td>
<td>$8,034</td>
<td>4.4%</td>
</tr>
<tr>
<td>Lighting Fixtures</td>
<td>$2,193</td>
<td>1.2%</td>
</tr>
<tr>
<td>HVAC</td>
<td>$8,760</td>
<td>4.8%</td>
</tr>
<tr>
<td>Insulation</td>
<td>$3,399</td>
<td>1.8%</td>
</tr>
<tr>
<td>Drywall</td>
<td>$8,125</td>
<td>4.4%</td>
</tr>
<tr>
<td>Painting</td>
<td>$6,005</td>
<td>3.3%</td>
</tr>
<tr>
<td>Cabinets and Countertops</td>
<td>$10,395</td>
<td>5.6%</td>
</tr>
<tr>
<td>Appliances</td>
<td>$3,619</td>
<td>2.0%</td>
</tr>
<tr>
<td>Tiles and Carpet</td>
<td>$8,363</td>
<td>4.5%</td>
</tr>
<tr>
<td>Trim Material</td>
<td>$3,736</td>
<td>2.0%</td>
</tr>
<tr>
<td>Landscaping and Sodding</td>
<td>$6,491</td>
<td>3.5%</td>
</tr>
<tr>
<td>Wood Deck or Patio</td>
<td>$1,918</td>
<td>1.0%</td>
</tr>
<tr>
<td>Asphalt Driveway</td>
<td>$2,729</td>
<td>1.5%</td>
</tr>
<tr>
<td>Other</td>
<td>$19,487</td>
<td>10.6%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$184,125</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

B. Khoshnevis

https://www.builderonline.com/building/its-about-time
Exotic Homes

http://www.mytechref.com/bf03fb06b5344a49.html

Reliability

- Human life at stake
  - Earthquakes
  - Fire
  - Tornados
- Need to conduct research
Research at NKU

- Biomimicking
- 3D printing
- 3D welding
Developing 3D House Printer

- **Fabrication of:**
  - **Mechanical Parts:**
    - Frame, Rails, Movements
    - Extrusion Heads
  - **Electrical Components:**
    - Motors
    - Drives
    - Wiring
  - **Programming**
    - 3D scanning, or Drawing
    - Slicing, interfacing with Computer (MACH 3)
Mechanical Parts

- **Frame:**
  - Made scalable: Trusses, lightweight but strong
  - Modular Rails: Extends in 3ft lengths
  - Gantry type

- **Writing Heads:**
  - Hard Phase: Clay, Plaster, Cement
  - Soft Phase: Rubbers, Plastics
  - Adhesives: Sprays

- **Reinforcements:**
  - Steel, Synthetic Fiber, Fiberglas, Hemp

Prototype of a 3D printer scaled down to 1:10 developed at NKU
Mechanical Components

[Images of mechanical components and diagrams]
Electrical Components

- Motors (8):
  - 3-phase AC servomotors
  - 2.4 N-m to 15 N-m torque (Extruders, and motion in x,y and z)
  - 0.75 to 2.2 kW (3000 to 1500 RPM)
  - 110-220V single phase motors with gearheads for mixers
  - Synchronized motion of 2 motors each for y and z directions)
  - Small motor for MIG welding guns for metal deposition)

- Drives
  - 8 Drives, each controlling one motor, communicating with computer

- Wiring
  - Over 450 terminals to connect with different gage wires
Programming

- MACH 3 for the Control of Machine
  - Mach 3 allows selection of pins used for
  - Direction, position and speed of the extruders
  - The thickness of the deposited material by control of the flow
  - Control of the thickness of the layers by the z direction elevation control

- 3D laser scanner for creating Models:
  - Objects can be scanned (e.g. making statues with the printer)
  - AutoCAD, SolidWorks, or Architectural software used to make models

- Cura for slicing of Models:
  - Can slice the models and tool paths are created
  - Generates G-code executable by MACH3
Materials Made

- Ceramics
  - Plaster, Clay and Cement

- Polymers:
  - Caulk
  - Plastic (being developed at this time)

- Metals:
  - Structural Steel
  - Bronze (TBD)
  - Stainless steel (TBD)
  - Aluminum

Allameh et al. [6]
Naturally Tough Material

- Mother of pearl and oyster are naturally tough
- Hard layers of calcium carbonate (aragonite)
- Soft interlayer of natural polymer
- Great resistance to dynamic shear, typical of earthquakes
- 8% elongation parallel to the plates

Allameh et al. [10]
Fabrication and Testing of Biomimicked Composites

- Fabricated biomimicked composites using:
  - Hard ceramic
  - Soft polymer
  - Reinforcement fiber

- Microstructural characterization

- Mechanical Tests:
  - Tensile, compressive, bending, Dynamic shear test
  - Determine critical factors that affect toughness
Materials

- Concrete, plaster and clay for hard layer
  - Ready mix of cement and sand
    - Quikrete, mortar mix No. 122.

- Polymers for soft layer
  - Spray adhesive from 3M (Rubber & Vinyl 80, consisting mostly of methylacetate, dimethyl ether, cyclohexane, and toluene), Gorilla Glue, Concrete bonding adhesive

- Synthetic and natural fiber for reinforcement
  - Carbon fiber, Tenax-A HTR40 F22 24K 1550tex
    - Tensile strength is 4.654 GPa, with a modulus of 248 GPa, elongation of 1.88% and a density of 1.81 g/cc. Th
    - Chopped in various nominal lengths of 2, 4, 8, 16, 32, and 150 mm.
    - Hemp: used in fabric form

<table>
<thead>
<tr>
<th>Hazardous Components</th>
<th>CAS No.</th>
<th>% by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, Silica, Quartz</td>
<td>14808-60-7</td>
<td>40-70*</td>
</tr>
<tr>
<td>Portland Cement</td>
<td>68997-15-1</td>
<td>10-30*</td>
</tr>
<tr>
<td>Lime</td>
<td>01305-62-0</td>
<td>5-10*</td>
</tr>
</tbody>
</table>
Microstructural Characterization

- BSE imaging with SEM performed
- Elemental dot maps obtained
- Details of interlayers observed

Elemental dot map (left) and BSE image (right) taken from the cross section of biomimicked sample, Allameh et al. [1]
EDX of Biomimicked Samples

- SEM imaging
  - Thickness of hard layer ~ 1-2 mm
  - Thickness of soft layer nm range

SE image (left) and X-ray diffraction graph (right) taken from the cross section of biomimicked sample, Allameh et al. [1]
Mechanical Testing

- Monotonic tensile and compressive loading
- Dynamic shear loading
- 4-point bend testing
- Combinatorial Research
  - Instron used
  - Load vs elongation
  - Load vs bending

Allameh et al. [4]
Micromechanical Testing

- Micro-samples cut across thin sections
- Tested in monotonic and cyclic loading
- Exploring the reliability of 3D welded rebars

a) Instron E-1000 Electropulse fatigue testing system, b) Microsample, c) sample mounted in grippers, d) Fracture surfaces after fatigue test [13]
Results

- Effect of type of hard layer
- Effect of type of soft layer
- Effect of type of reinforcement
  - Effect of shape, geometry and orientation
  - Effect of volume fraction (Fiber loading)
  - Effect of length (continuous vs discontinuous at various lengths)
- Reliability of 3D welded steel structures for rebars
  - Tensile testing
  - Fatigue testing
Effects of Various Factors on Structural Composites

- **Effect of Fiber Loading:** As % of fiber increases so does the strength [5]
- **Effect of Fiber Length:** As Length of fiber increases so does the strength [8]
- **Effect of Type of Adhesive:** Concrete Bonding Adhesive best [8]
- **Effect of Layer Thickness:** Thinner layers provide higher toughness values [8]
- **Effect of Type of Composite:** Highest fracture energy for concrete-carbon fiber with Gorilla™ glue [10]
- **Combinatorial Research:** No sudden drop in strength for biomimicked sample [9]
- **Flexural Stress vs Strain for 3D Printed Composites:**
Reliability of 3D Welded Steel for Rebars

Effect of orientation on Strength
Highest strength along tool path, lowest across the thickness of the weld bead [11]

Effect of Cooling rate: Slightly higher strength for the fast cooled top of the weld bead vs. slow-cooled bottom of the bead in contact with concrete [12]

Backscattered electron (BSE) image of the cross section of 3D welded bead showing no noticeable porosity [12]
Outcomes

- Biomimicking provides toughness [1-10]
- 3D printing-based Combinatorial Composite Research Possible [9]
- 3D welding produces structures that have
  - Sufficient strength [11-12]
  - Sufficient ductility [11-12]
  - Sufficient fatigue resistance [13]
  - Steel Reinforced Concrete is possible and reliable with 3D welding [1-13]
Other Aspects

- Social
- Economical
- Trends
- Innovations
Acknowledgement

- Drs. Diana McGill, Dean, CAS, and Dr. Sharmanthie Fernando, Chair, PGET, for financial support
- Roger Miller, Technical Assistance, Lab Manager, Instructor, PGET, NKU
- Mike Lehrter, Technical Assistance, Lab Manager, PGET, NKU
- NKU Students who provided various types of support
References


