Manufacturing Dream Homes Digit by Digit

Digital Homes

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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): $11

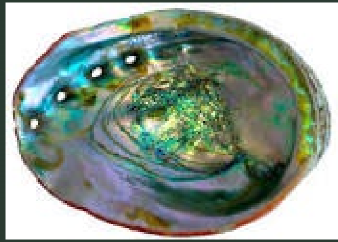
https://all3dp.com/2/3d-printed-house-cost/

https://www.businessinsider.com/3d-homes-that-take-24-hours-and-less-than-4000-to-print-2018-9

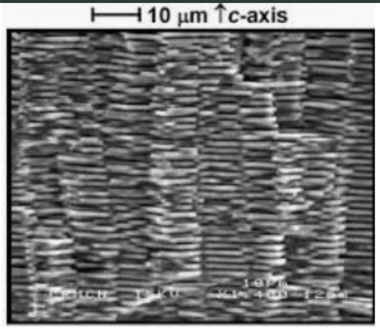
Biomimicking

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

DNA self-assembly
doye.chem.ox.ac.uk



https://news.wisc.edu/mother-of-pearls-genesis-identified-in-minerals-transformation/

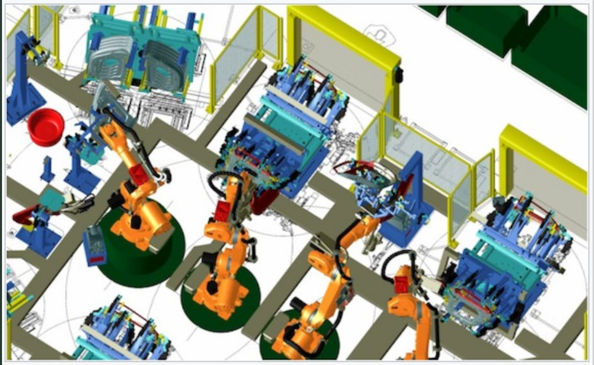


Pearl | Causes of Color
webexhibits.org

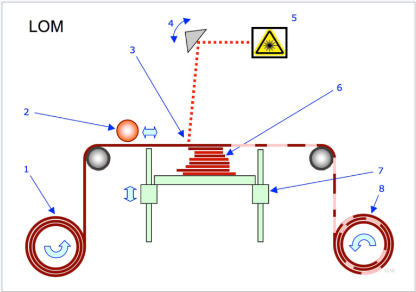
Digital Manufacturing

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

Digital Manufacturing and Logistic...
greatnorthlabs.com



Robcad is a popular software used in digital manufacturing. Models of automated machinery and production lines can be created and simulated in real time.



Example of Laminated object manufacturing process Laminated object manufacturing: principle drawing. 1 Supply roll. 2 Heated laminated roll. 3 Laser cutting beam. 4 Prism steering device. 5 Laser. 6 Laminated shape. 7 Movable table. 8 Waste roll (with cutout shapes).

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

Tools

- 3D printers
- 3D welder
- Contour Crafting

https://www.autodesk.com/redshift/3d-printing-concrete/

https://www.autodesk.com/redshift/3d-printing-concrete/

First 2-Story Building in Dubai

https://www.youtube.com/watch?v=69HrqNnrfh4

https://www.youtube.com/watch?v=69HrqNnrfh4

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/

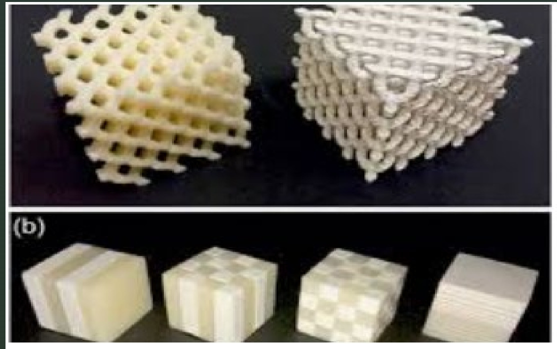
Materials

- Metals
- Polymers
- Ceramics
- Composites

3D printing with metals - technologies ...
weekly-geekly.github.io

Figure 4 technology by 3D Systems
additivemanufacturingtoday.com

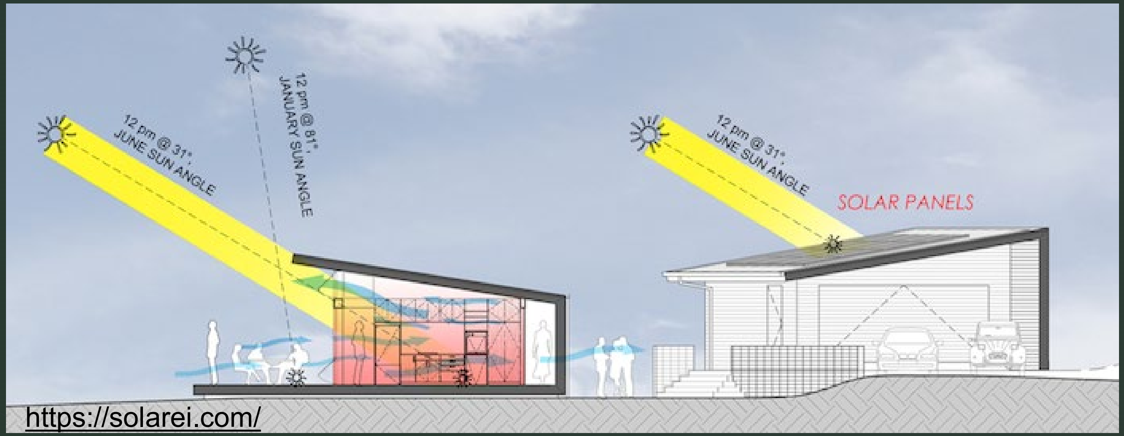
StoneFlower 3.0 Clay and Ceramic 3D ...
3dprms.com · In stock



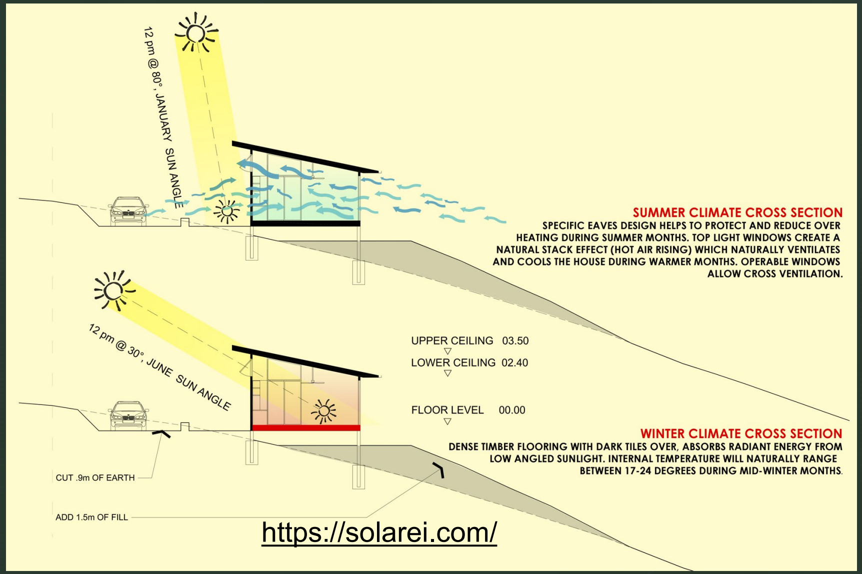
3D printing of polymer matrix ...
sciencedirect.com

Desired Functionality

- Natural air conditioning
- Green
- Ascetically pleasing



https://solarei.com/



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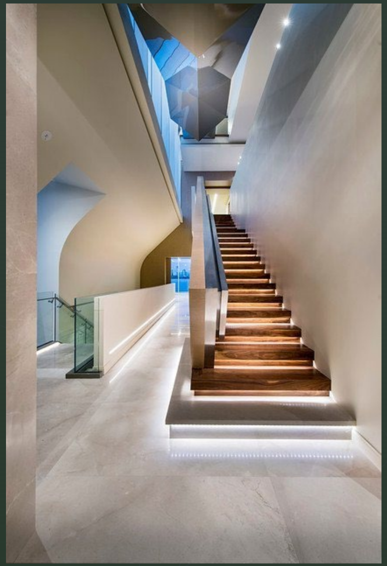


https://www.pinterest.ca/pin/776026579515942192/

Challenges

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

Benefits: Resistance to Earthquakes

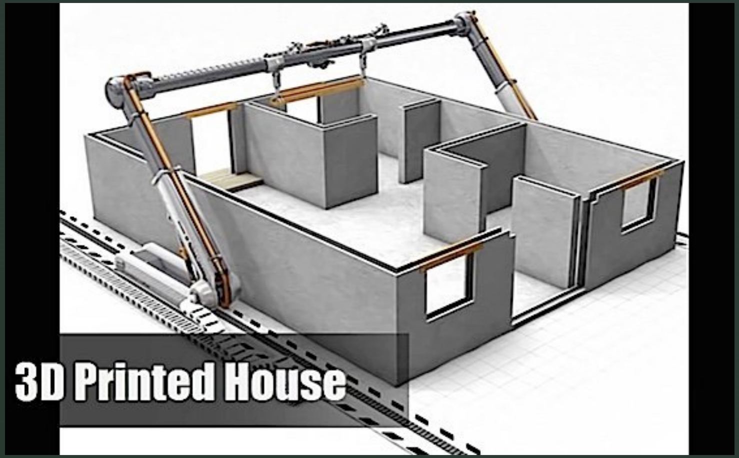
- Integrative Approach to house building
- Elimination of interfaces, joints, weak links
- Use of toughening schemes
  - Resistance against dynamic shear forces typical of earthquakes
  - Resistance against rain, heat
  - Resistance against tilting
  - Elimination of 10,000 killed and 400,000 injured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

Earthquake in Chile, https://www.leftcom.org/en/articles/2010-03-10/the-situation-in-chile-after-the-earthquake

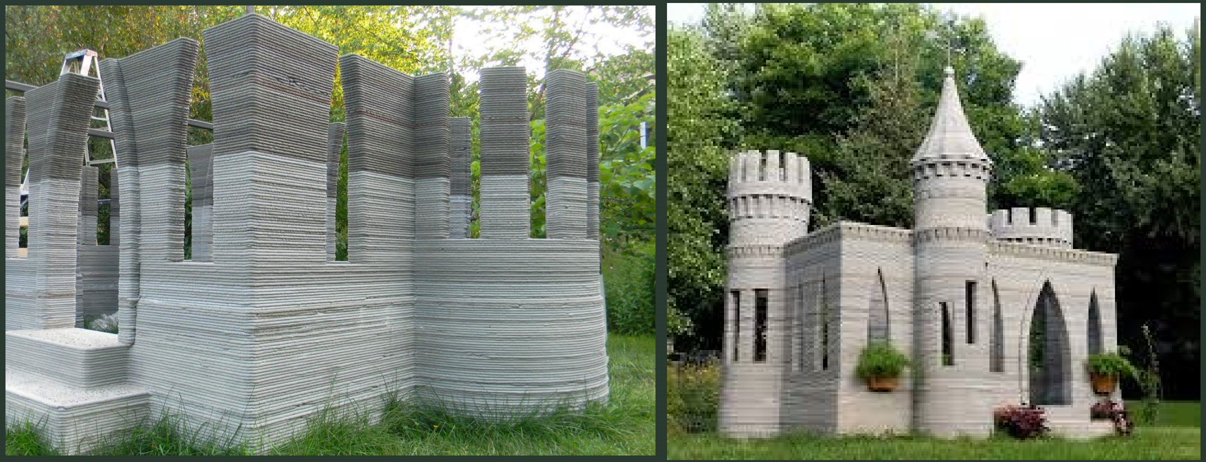
1906 Earthquake in San Francisco, https://fineartamerica.com/shop/canvas+prints/1906+san+francisco+earthquake

Quick Process

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



https://www.ediweekly.com/3d-printed-homes-24-hours-printed-site-printed-villas-offices-floating-saunas/



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

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

- B. Khoshnevis

Table 1. Single Family Price and Cost Breakdowns 2011 National Results		
Average Lot Size:		20,614 sq ft
Average Finished Area:		2,311 sq ft
I. Sale Price Breakdown	**Average**	**Share of Price**
A. Finished Lot Cost (incl. financing cost)	$67,551	21.7%
B. Total Construction Cost	$184,125	59.3%
C. Financing Cost	$6,669	2.1%
D. Overhead and General Expenses	$16,306	5.2%
E. Marketing Cost	$4,645	1.5%
F. Sales Commission	$10,174	3.3%
G. Profit	$21,148	6.8%
Total Sales Price	**$310,619**	**100.0%**
II. Construction Cost Breakdown	**Average**	**Share of Construction Cost**
Building Permit Fees	$3,107	1.7%
Impact Fee	$2,850	1.5%
Water and Sewer Inspection	$2,952	1.6%
Excavation, Foundation, and Backfill	$17,034	9.3%
Steel	$1,012	0.5%
Framing and Trusses	$24,904	13.5%
Sheathing	$2,142	1.2%
Windows	$6,148	3.3%
Exterior Doors	$2,150	1.2%
Interior Doors and Hardware	$2,883	1.6%
Stairs	$1,052	0.6%
Roof Shingles	$5,256	2.9%
Siding	$8,739	4.7%
Gutters and Downspouts	$870	0.5%
Plumbing	$10,990	6.0%
Electrical Wiring	$8,034	4.4%
Lighting Fixtures	$2,193	1.2%
HVAC	$8,760	4.8%
Insulation	$3,399	1.8%
Drywall	$8,125	4.4%
Painting	$6,005	3.3%
Cabinets and Countertops	$10,395	5.6%
Appliances	$3,619	2.0%
Tiles and Carpet	$8,363	4.5%
Trim Material	$3,736	2.0%
Landscaping and Sodding	$6,491	3.5%
Wood Deck or Patio	$1,918	1.0%
Asphalt Driveway	$2,729	1.5%
Other	$19,487	10.6%
Total	**$184,125**	**100.0%**

https://www.builderonline.com/building/its-about-time_o

Exotic Homes

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

https://www.thetravel.com/crazy-homes-that-look-straight-out-of-the-future/

Reliability

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

Research at NKU

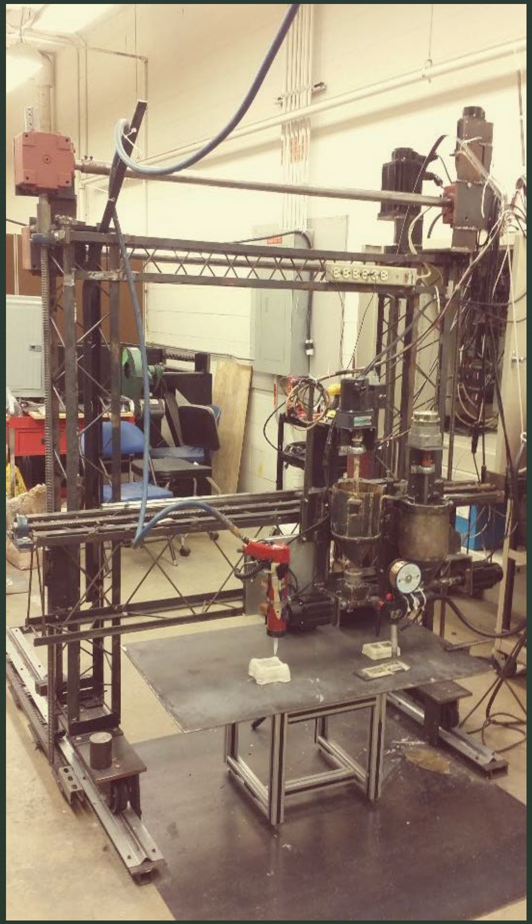
- Biomimicking
- 3D printing
- 3D welding

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)

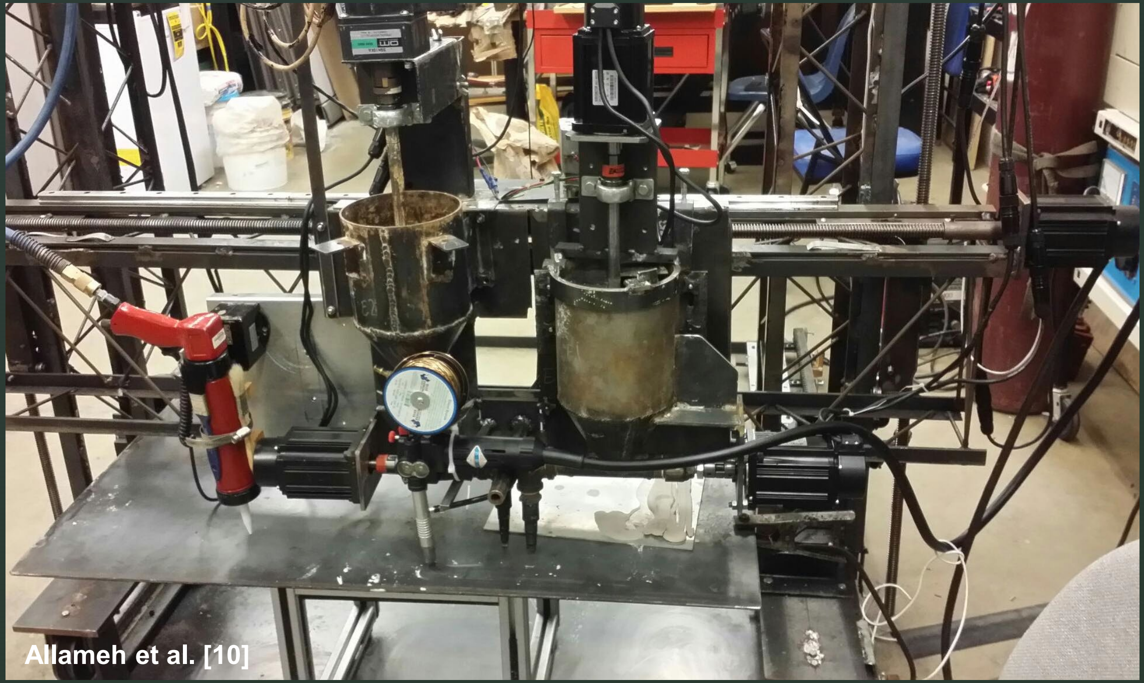
Mechanical Parts

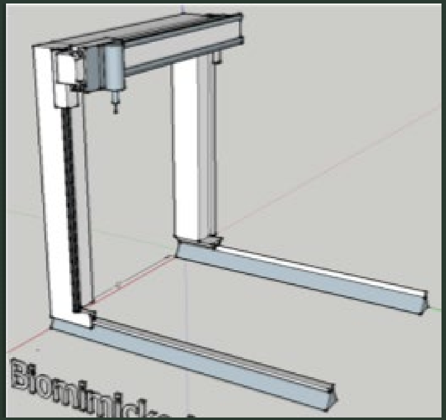
- Frame:
  - Made scalable: Trusses, lightweight but strong
  - Modular Rails: Extends in 3ft lengths
  - Gantry type
- Writing Heads:
  - Hard Phase: Clay, Plaster, Cement
  - Soft Phase: Rubbers, Plastics
  - Adhesives: Sprays
  - Reinforcements:
    - Steel, Synthetic Fiber, Fiberglas, Hemp

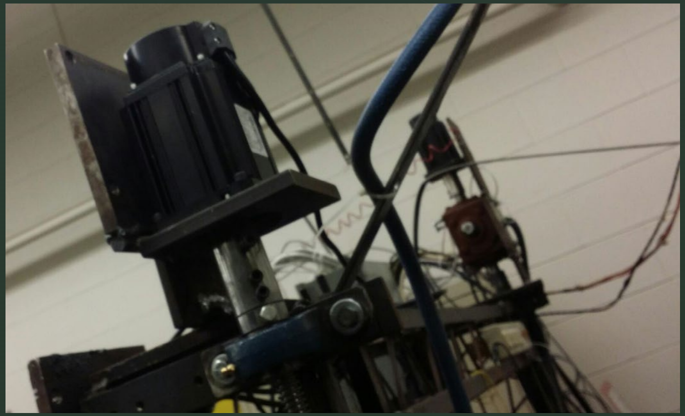


Prototype of a 3D printer scaled down to 1:10 developed at NKU

Mechanical Components

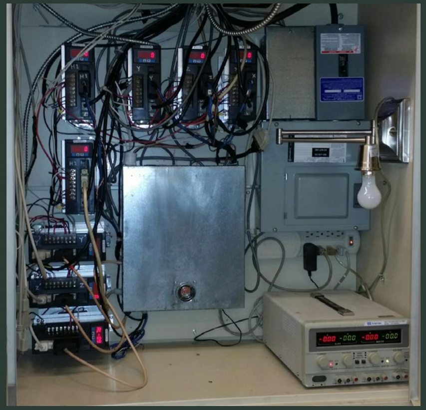

Allameh et al. [10]





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

3D Systems, Laser Scanner Model [8]

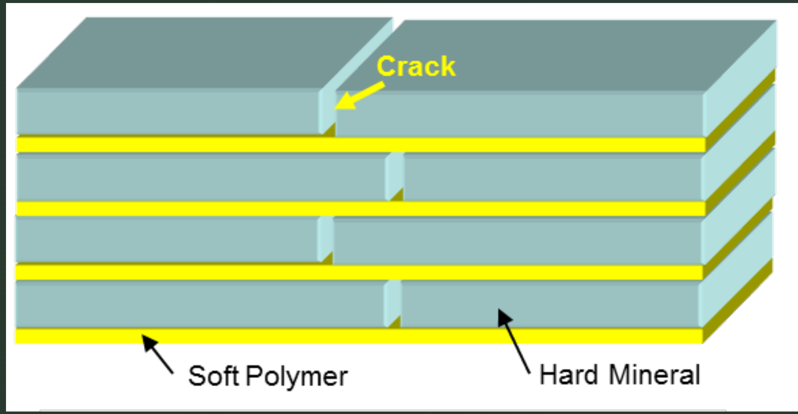
Materials Made

- 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]

Nacre

- 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

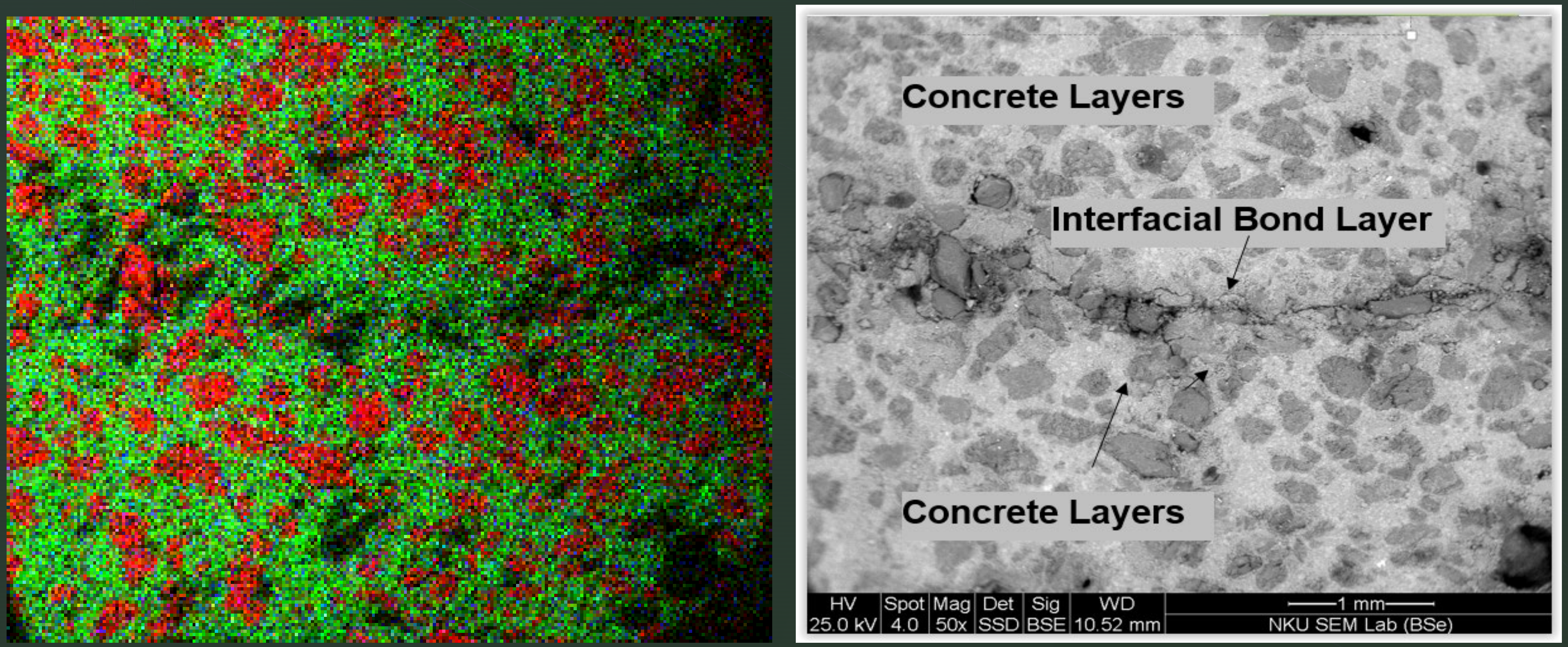
Materials

- 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

Hazardous Components	CAS No.	% by Weight
Sand, Silica, Quartz	14808-60-7	40-70*
Portland Cement	65997 15 1	10-30*
Lime	01305-62-0	5-10*

Microstructural Characterization

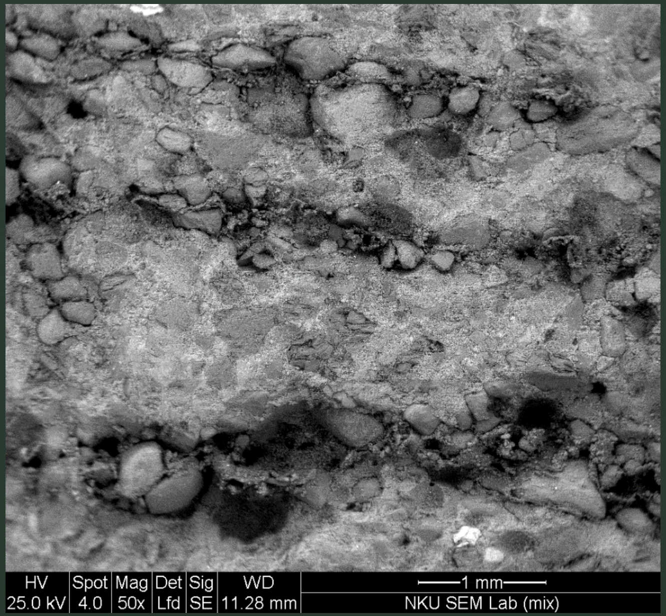
- BSE imaging with SEM performed
- Elemental dot maps obtained
- Details of interlayers observed

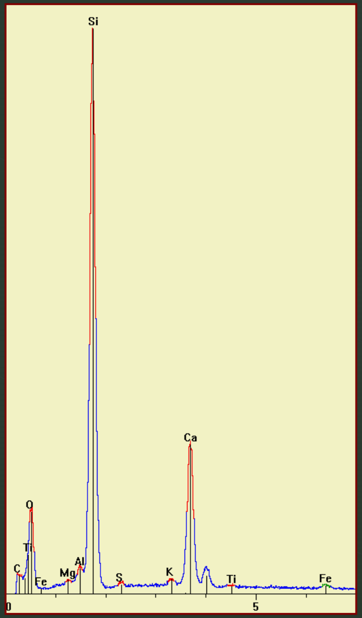


Elemental dot map (left) and BSE image (right) taken from the cross section of biomimicked sample, Allameh et al. [1]

EDX of Biomimicked Samples

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

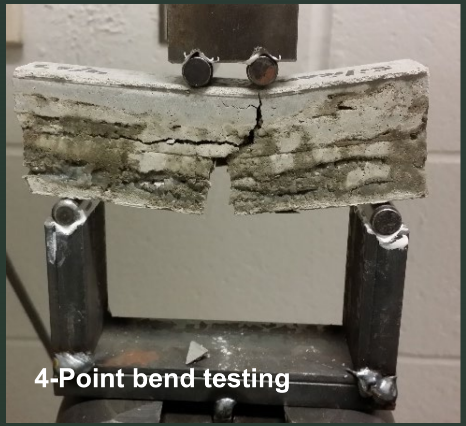




SE image (left) and X-ray diffraction graph (right) taken from the cross section of biomimicked sample, Allameh et al. [1]

Mechanical Testing

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


4-Point bend testing


Fracture Surfaces of dog-bone shaped samples after Tensile Testing


Shake Table with Sample Mounted


Dynamic Shear Testing

Allameh et al. [4]

Micromechanical Testing

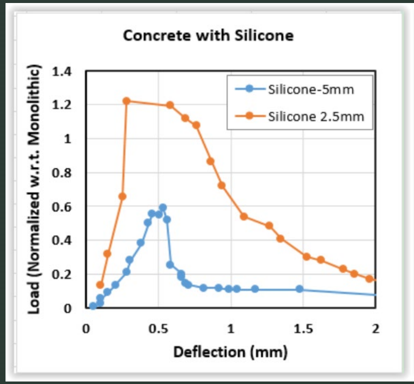
- Micro-samples cut across thin sections
- Tested in monotonic and cyclic loading
- Exploring the reliability of 3D welded rebars

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

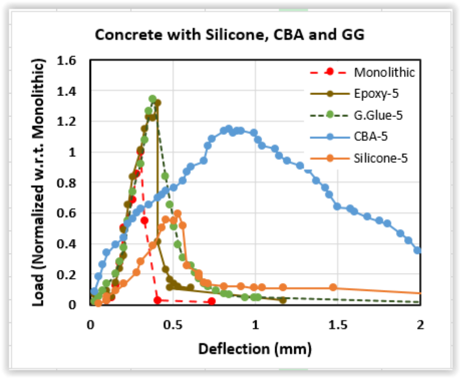
Results

- 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

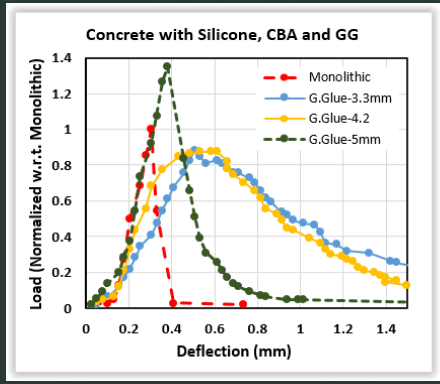
Effects of Various Factors on Structural Composites



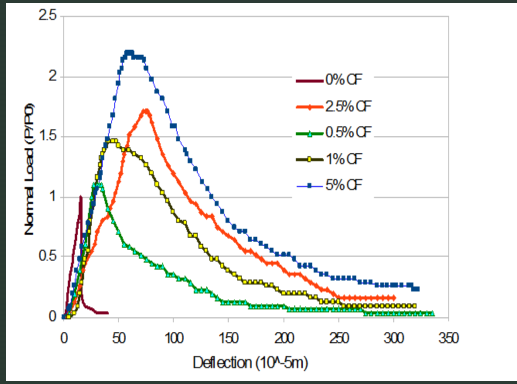
Effect of Layer Thickness
Thinner layers provide higher toughness values [8]



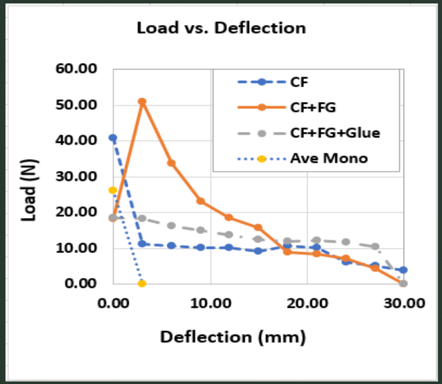
Effect of Type of Adhesive:
Concrete Bonding Adhesive best [8]



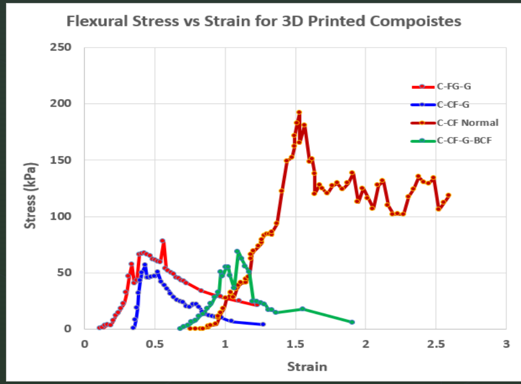
Effect of Fiber Length:
As Length of fiber increases so does the strength [8]



Effect of Fiber Loading:
As % of fiber increases so does the strength [5]

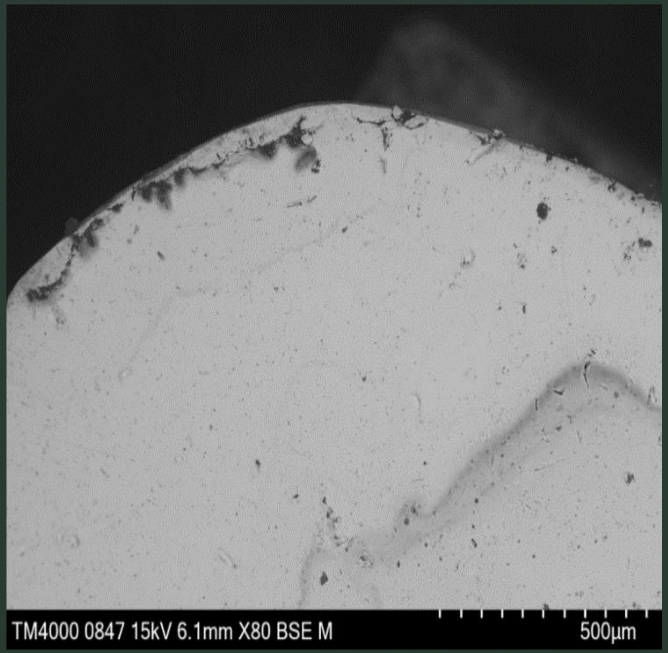


Combinatorial Research:
No sudden drop in strength for biomimicked sample [9]

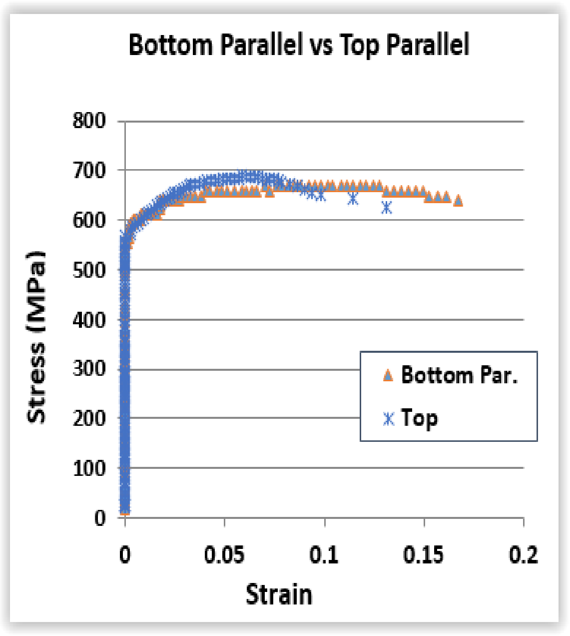


Effect of Type of Composite:
Highest fracture energy for concrete-carbon fiber with Gorilla™ glue [10]

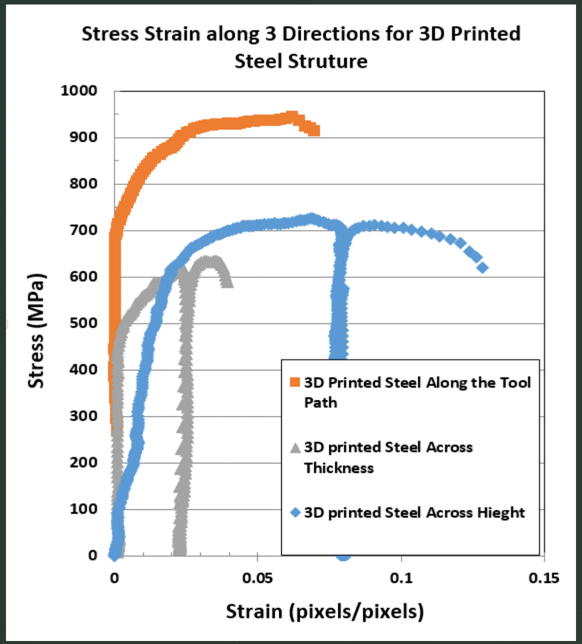
Reliability of 3D Welded Steel for Rebars



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



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]



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

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

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3. S. M. Allameh, T. Ogonek and Paul Cooper, "Fabrication and Characterization of Bio-Inspired Structural Composites," Proceedings of ASME 2008 International Mechanical Engineering Congress and Exposition, IMECE2008-66778 Oct. 31-Nov. 6th, Boston, MA, 12, pp. 369-372, 2008.(SL), doi: 10.1115/IMECE2008-66778

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5. Hussain Alghahtani and Seyed M. Allameh, "Effect of Fiber Form and Volume Fraction on Fiber-Reinforced Biomimicked Composites," Proceedings of 2012 ASME International Mechanical Engineering Congress and Exposition, IMECE2012-85718, Nov. 9-15 2012, Houston, TX (SL), doi: 10.1115/IMECE2012-85718.

6. S. M. Allameh, "On the Development of a 3D Printer for Combinatorial Structural Composite Research," Proceedings of 2015 ASME International Mechanical Engineering Congress and Exposition, IMECE2015-50962, Nov. 13-19 2015, Houston, TX, doi: 10.1115/IMECE2015-50962.

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