Manufacturing Dream Homes Digit by Digit

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): $11

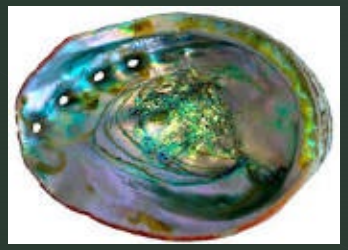
https://all3dp.com/2/3d-printed-house-cost/

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

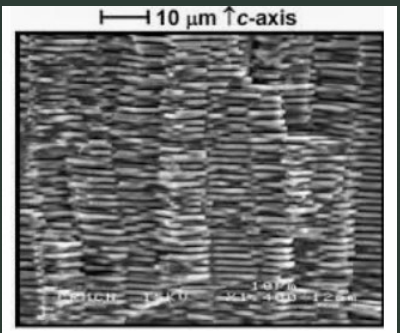
Biomimicking

- 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/

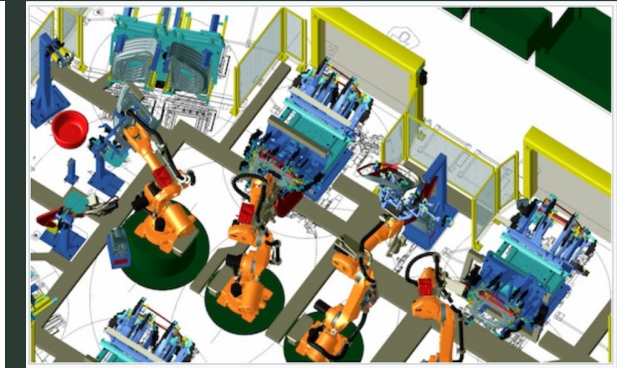


Pearl | Causes of Color
webexhibits.org

Digital Manufacturing

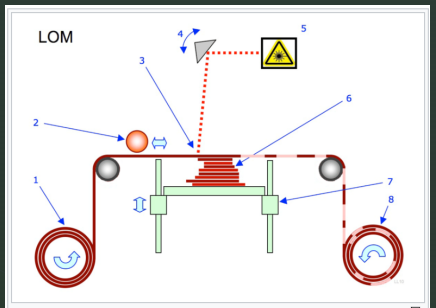
- Similar to Printing
- Deposit Material
- Desired location
- Computer Design

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.

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



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).

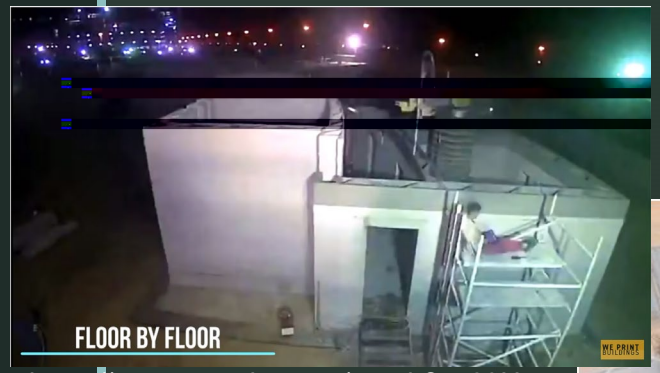
Tools

- 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

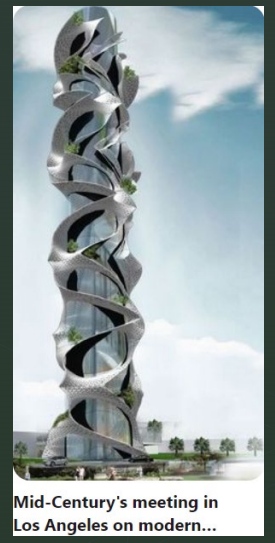
Benefits

- 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/

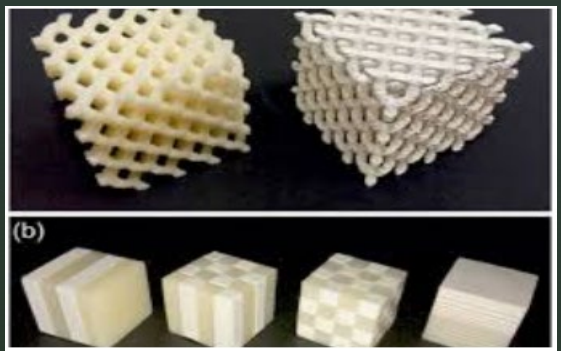
Materials

- Metals
- Polymers
- Ceramics
- Composites

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

Figure 4 technology by 3D Systems
additivemanufacturingtoday.com

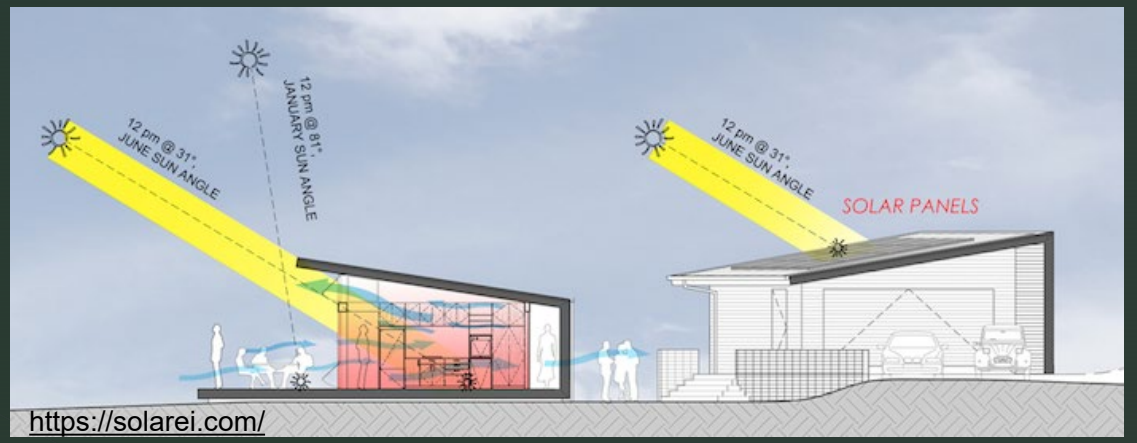
StoneFlower 3.0 Clay and Ceramic 3D ...
3dprms.com · In stock



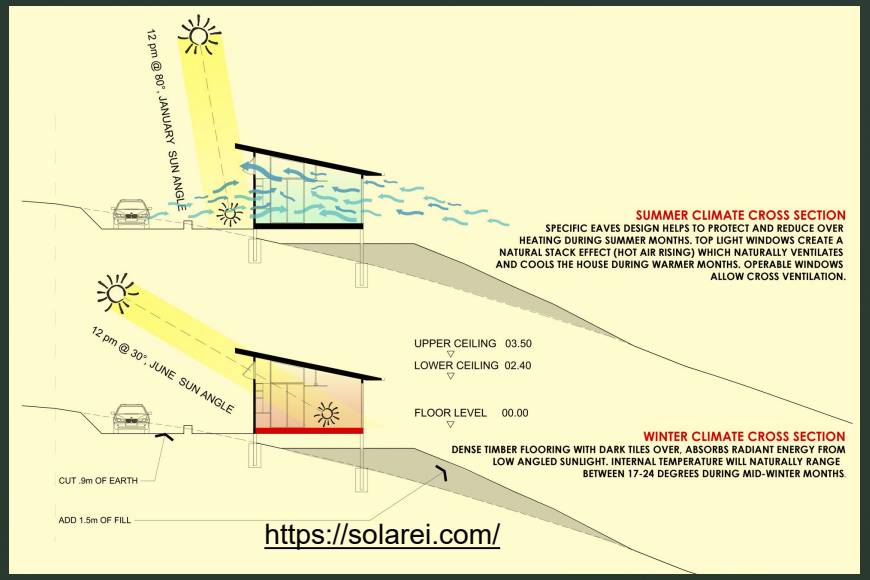
3D printing of polymer matrix ...
sciencedirect.com

Desired Functionality

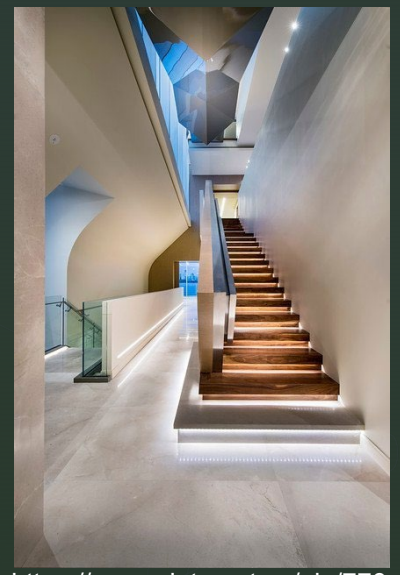
- Natural air conditioning
- Green
- Ascetically pleasing



https://solarei.com/



https://solarei.com/



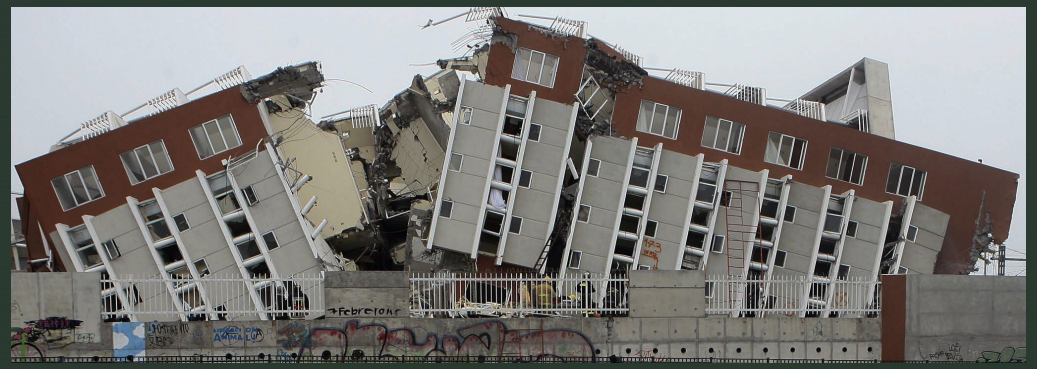
https://www.pinterest.ca/pin/776026579515942192/

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

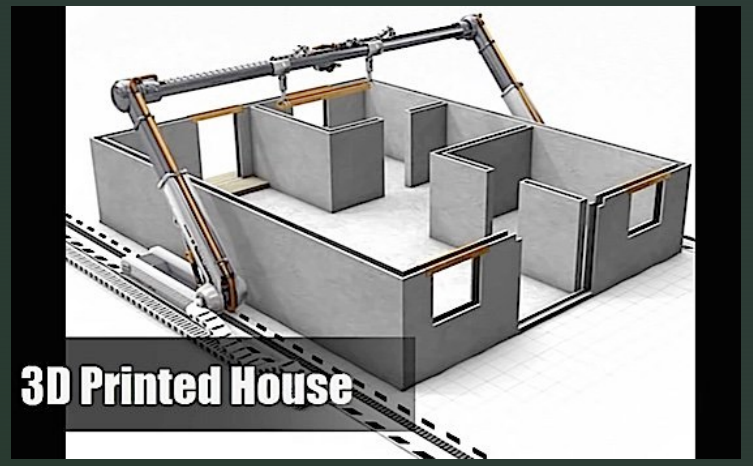


Earthquake in Chile, https://www.leftcom.org/en/articles/2010-03-10/the-situation-in-chile-after-the-earthquake

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

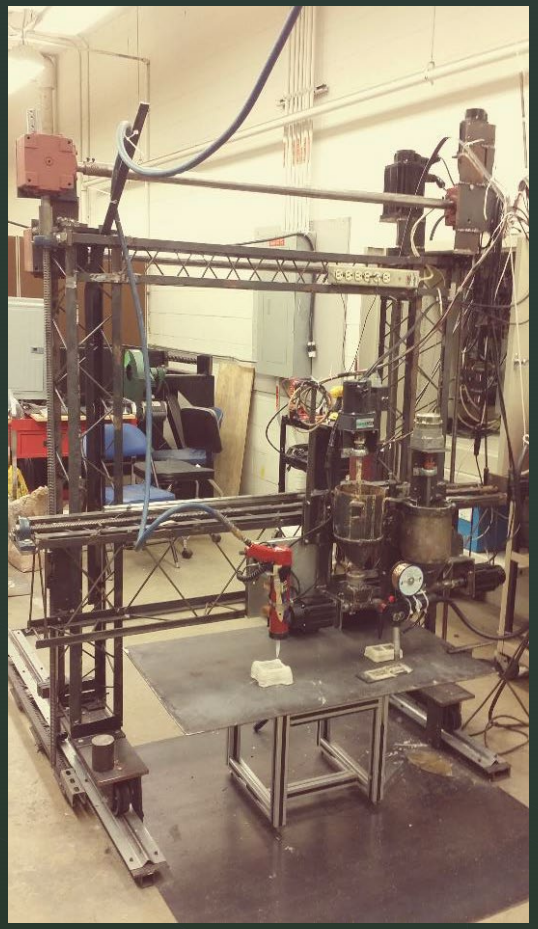
- Biomimicking
- 3D printing
- 3D welding

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)

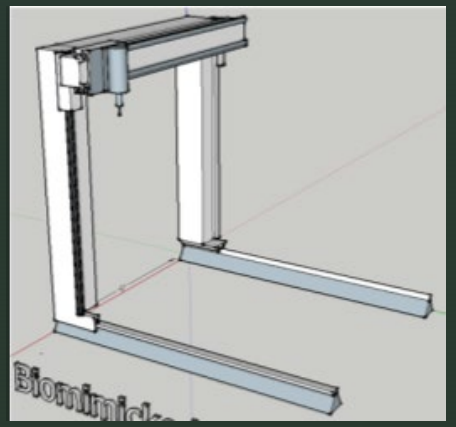
Mechanical Parts

- 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



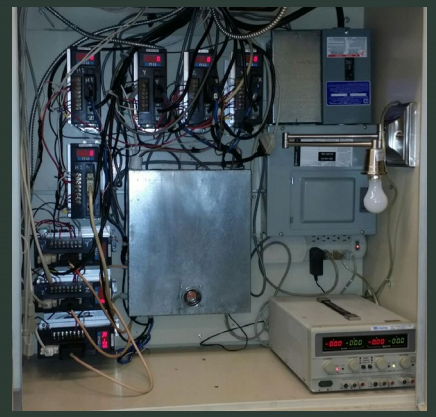
Prototype of a 3D printer scaled down to 1:10 developed at NKU

Mechanical Components



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



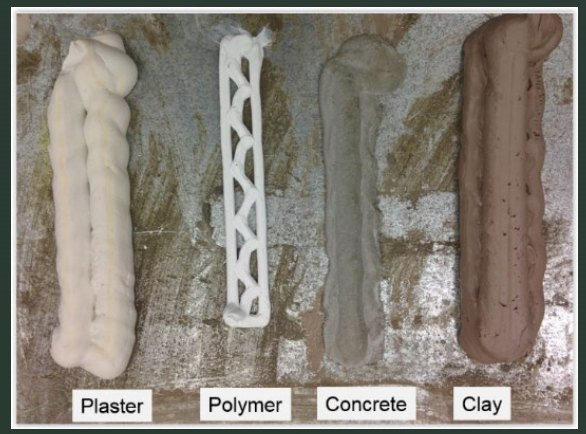
Programming

- 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

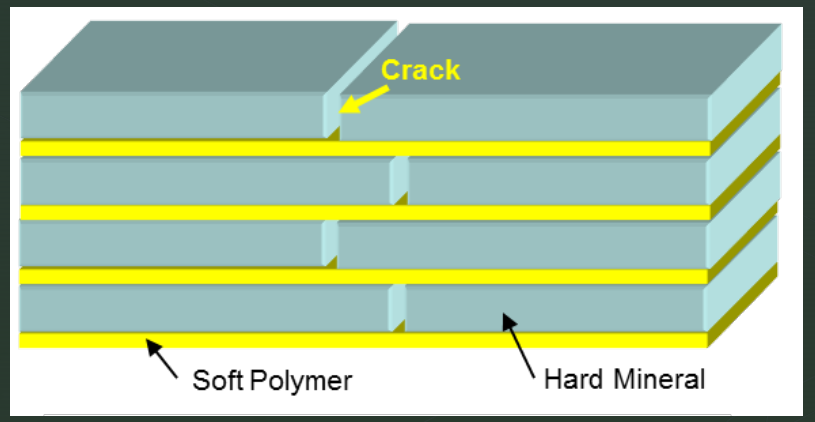
- Ceramics
  - Plaster, Clay and Cement
- Polymers:
  - Caulk
  - Plastic (being developed at this time)
- Metals:
  - Structural Steel
  - Bronze (TBD)
  - Stainless steel (TBD)
  - Aluminum



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

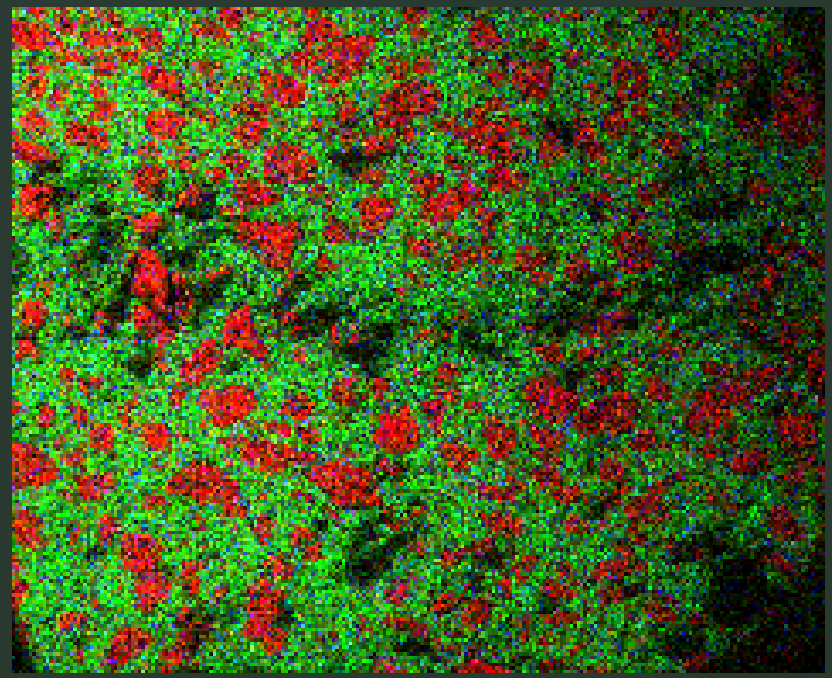
Materials

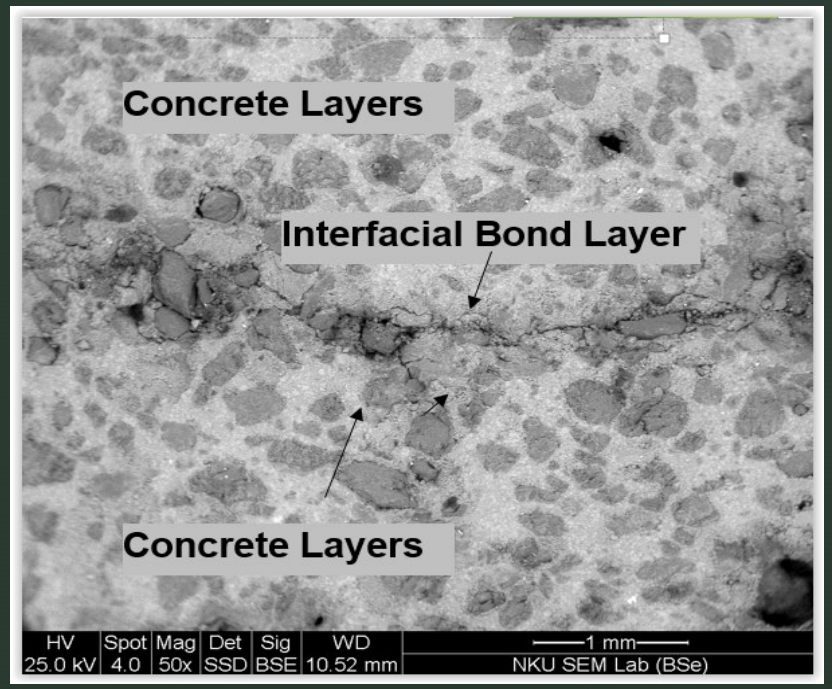
- Concrete, plaster and clay for hard layer
  - Ready mix of cement and sand
    - Quikrete, mortar mix No. 122.
- Polymers for soft layer
  - Spray adhesive from 3M (Rubber & Vinyl 80, consisting mostly of methylacetate, dimethyl ether, cyclohexane, and toluene), Gorilla Glue, Concrete bonding adhesive
- 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

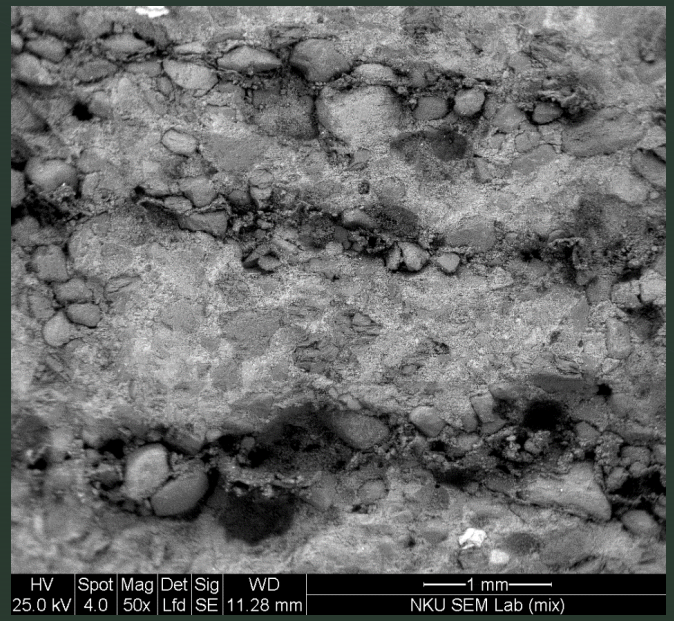


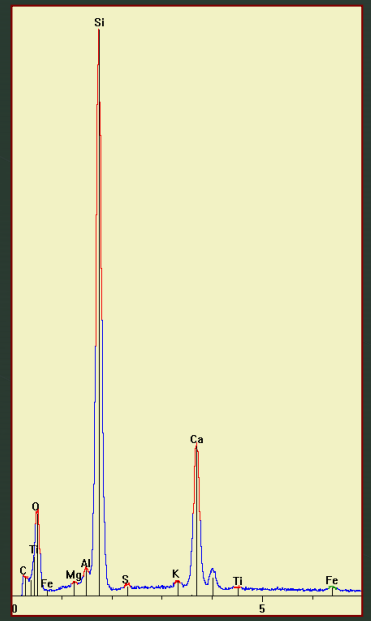


Elemental dot map (left) and BSE image (right) taken from the cross section of biomimicked sample, Allameh et al. [1]

EDX of Biomimicked Samples

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

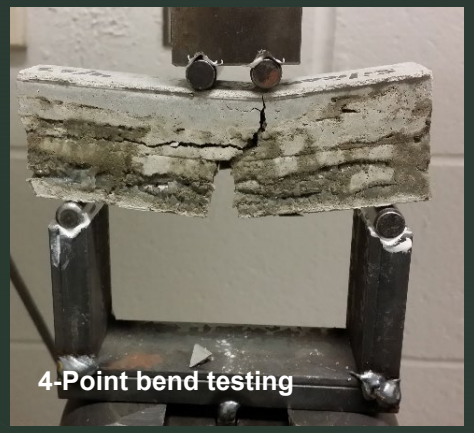




SE image (left) and X-ray diffraction graph (right) taken from the cross section of biomimicked sample, Allameh et al. [1]

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

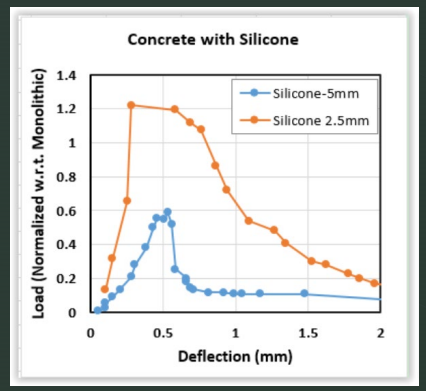
- Micro-samples cut across thin sections
- Tested in monotonic and cyclic loading
- Exploring the reliability of 3D welded rebars

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

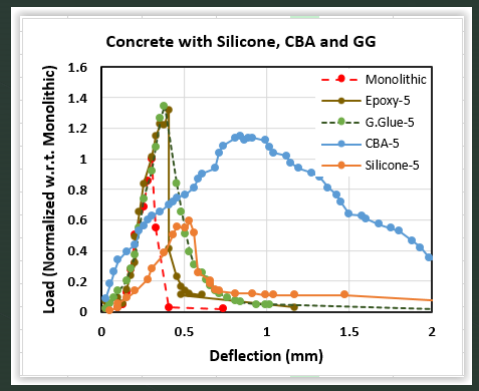
Results

- 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

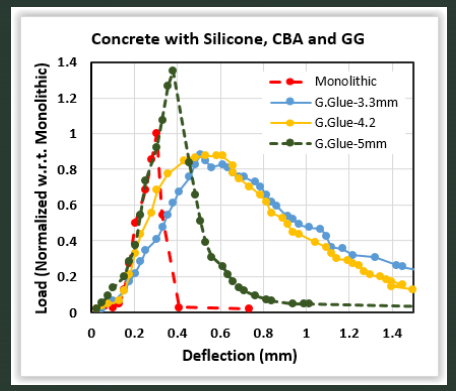
Effects of Various Factors on Structural Composites



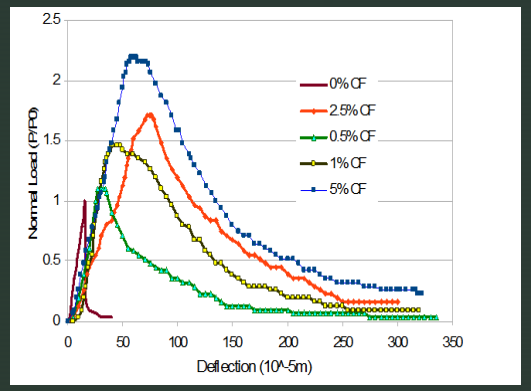
Effect of Layer Thickness
Thinner layers provide higher toughness values [8]



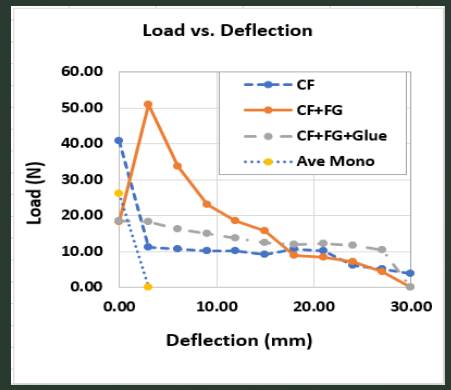
Effect of Type of Adhesive:
Concrete Bonding Adhesive best [8]



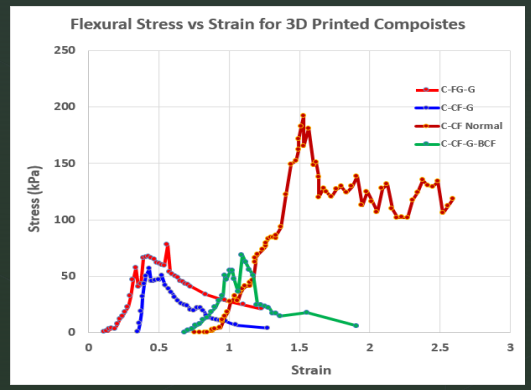
Effect of Fiber Length:
As Length of fiber increases so does the strength [8]



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

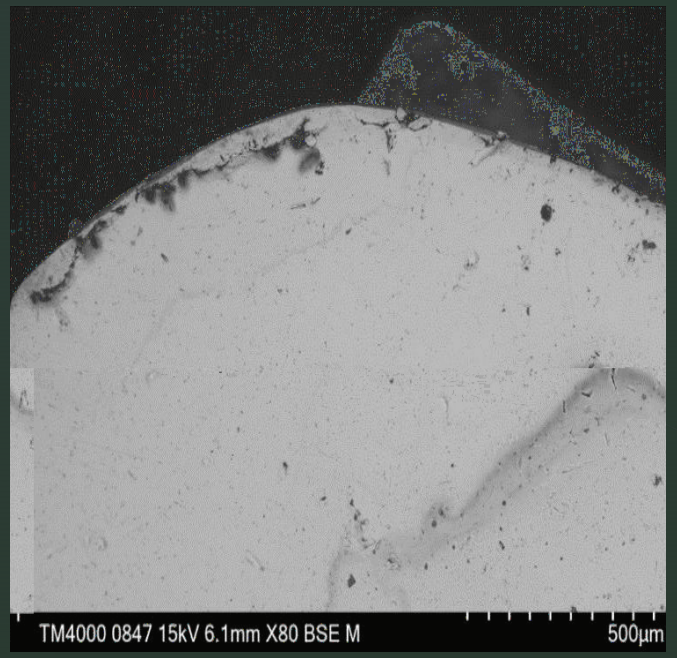


Combinatorial Research:
No sudden drop in strength for biomimicked sample [9]

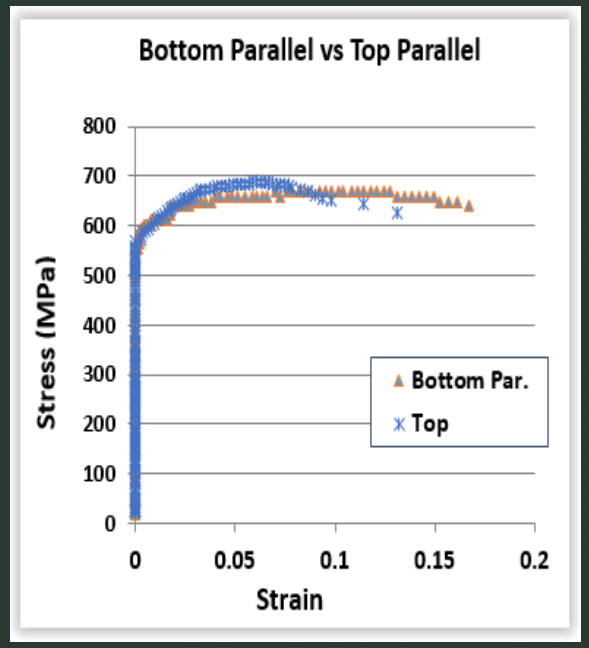


Effect of Type of Composite:
Highest fracture energy for concrete-carbon fiber with Gorilla™ glue [10]

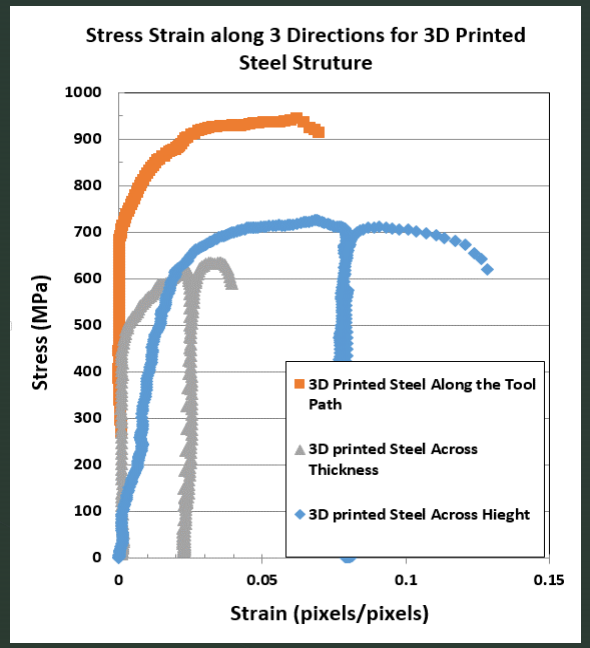
Reliability of 3D Welded Steel for Rebars



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

References

1. S.M. Allameh, M. Sadat-Hossieny and P. Cooper, "Instrumentation of RVM1 Robots for Developing Biologically Inspired Materials," Proceedings of 2006 ASEE Annual Conference and Exposition, Chicago, IL June 19-21 2006 (SL)

2. S. M. Allameh, T. Ogonek and Paul Cooper, "Synthesis and Characterization of Biomimicked Structural Composites," Proceedings of 2007 ASEE Annual Conference and Exposition, AC 2007-2581, June 24-27, 2007, Honolulu, HI

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

4. S.M. Allameh and M. Summe, "Mechanical Properties of Hemp-Reinforced Biomimicked Composites," Proceedings of 2010 ASME International Mechanical Engineering Congress and Exposition, IMECE2010-38440, Nov. 12-18,2010, Vancouver, BC (SL), doi: 10.1115/IMECE2010-38440

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.

7. S. M. Allameh, "Effect of Reinforcement Fiber Length on the Mechanical Behavior of Biomimicked Composites," Proceedings of 2016 ASME International Mechanical Engineering Congress and Exposition, IMECE2016-65202, Nov. 11-17 2016, Phoenix, AZ.

8. S. M. Allameh, "ON THE APPLICATION OF BIOMIMICKED COMPOSITES IN 3D PRINTED ARTIFACTS," Proceedings of 2017 ASME International Mechanical Engineering Congress and Exposition, IMECE2016-65202, Nov. 3-9 2017, Tampa, FL.

9. S.M. Allameh, R. Miller, and A. Muzaini, "Combinatorial Investigation of Mechanical Properties of Biomimicked Composites," Proceedings of 2019 ASME International Mechanical Engineering Congress and Exposition, IMECE2019-10395, Nov. 8-14, Salt Lake City, UT

10. S.M. Allameh, Roger Miller, and H. Allameh, "Mechanical Properties of 3D printed Biomimicked Composites," Proceedings of 2018 ASME International Mechanical Engineering Congress and Exposition, IMECE2018-86309, Nov. 9-15, Pittsburgh, PA.

References

11. S.M. Allameh, B. Harbin and B. Leininger "Mechanical Properties of 3D printed metals" Proceedings of 2018 ASME International Mechanical Engineering Congress and Exposition, IMECE2018-86310, Nov. 9-15, Pittsburgh, PA.

12. 100. S.M. Allameh and M. Ortiz Rejon, "Mechanical Properties of Steel Printed in Ceramics," Proceedings of 2019 ASME International Mechanical Engineering Congress and Exposition, IMECE2019-10392, Nov. 8-14, Salt Lake City, UT.

13. 101. S.M. Allameh, A. Lenihan, R. Miller, and H. Allameh, "Fatigue Properties of 3D Welded Thin Structions," Submitted to 2020 ASME International Mechanical Engineering Congress and Exposition, IMECE2020-23135, Nov. 16-19, Portland, OR.