























Determination of Hardened Performance of 3D Printed Concrete for Structural Validation

Eric Kreiger, PE
Structural Lead for Additive Construction
ERDC Construction Engineering Research Laboratory (CERL)
Eric.L.Kreiger@usace.army.mil

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US Army Corps of Engineers ®

On the Development of New Technologies

What is the worst thing about developing of new technologies?

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FAILURE

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What is the best thing about developing of new technologies?

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OVERCOMING FAILURE

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Don't be afraid of Failure!

- The development of new technologies will be filled with:
  - Growing pains
  - Mistakes
  - And Failure

Be Willing to Take Risks!

Don't be afraid to Adapt!

- The first solution is most assuredly not the right solution.
- Your acceptable solution may not be the only solution and may never be your final solution.
- Success after failure is limited by ones ability to adapt.

"Ever tried. Ever Failed. No matter.
Try Again. Fail Again. Fail better."

Samuel Beckett
Worstward Ho!

On the Development of New Technologies

We want to fail now during development, rather than later.

Champlain Towers S Collapse in Surfside, FL

On the Development of New Technologies

Industry-accepted construction materials

- 3/8" aggregate
- Cement
- Sand
- Water
- Additives
- Reinforcement

Force Protection

Buildings (b-huts)

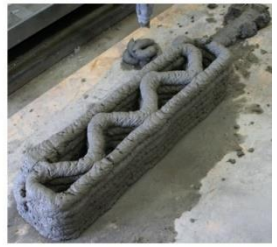
Fighting position – printed walls, roof, foundation

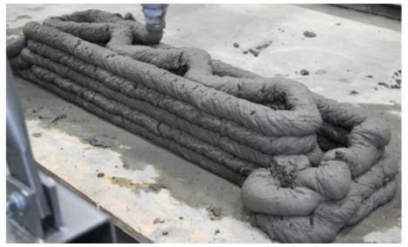
Gap Crossings

On the Development of New Technologies

Iteration of mixes





Plastic collapse


Elastic Buckling

Cracking



Quality Assurance and Quality Control testing ensure that failures have a low probability of occurrence.

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Why are Validation Methods Required?

There is not enough data to support equivalency to current materials and design methods

- A 3D printed element can NOT be designed based on
  - ACI 318
  - TMS 402
- There is no structural code.
- Different or modified design calculations are required.
  - large amount of material data from
  - numerous research institutes
- Lack of sufficient number of structural studies on components and systems tested against design requirements or other structural systems.

Why are Validation Methods Required?

Code section that allows for Alternative material, design or method

- IBC 104.11, IRC 104.11, UFC 1-200-01 Section 104.11
- Requires sufficient validation to substantiate that proposed technology meets design requirements
  - QA Testing
  - Previous Data
  - QC Testing
- Test Report provided to authority having jurisdiction (e.g. Building official), and engineer of record for review.

Can Existing Tests be Used for Validation?

MATERIALS TESTS

Answer: Some existing standards can be used for material development, but will need modifications to procedures and/or specimens to be representative of actual behavior.

STRUCTURAL TESTS

Answer: Most structural test methods can be performed with little modification. It comes down to which ones are appropriate for validation of actual as-built performance.

Case Studies

Enhanced Barracks Hut (Champaign, IL)

- Dates: 01 Aug – 3 Aug, 2018
- 512 ft^2 (47.6 m^2) building
- Morphing 9 ft (2.75 m) tall print-in-place walls
- Continuous overnight printing operations
- The walls printed in under 48 hours elapsed time, and 14 hours print time, w/ 8 hour break.
- Contracted with Skidmore, Owings, & Merrill (SOM) for design

Pedestrian Bridge (Camp Pendleton, CA)

- Dates: 03 Dec – 13 Dec 2018
- Additively Constructed Concrete bridge
- 33 ft (10 m) gap crossing pre-printed near site
- 3 spans, 2 piers
- Designed in 3 months
- Printed and emplaced in 6 days

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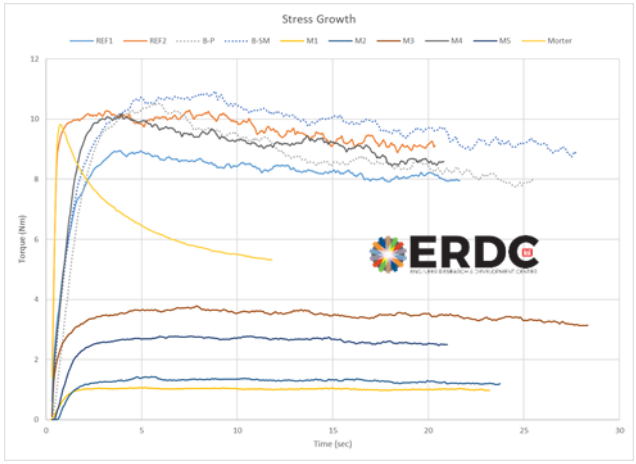
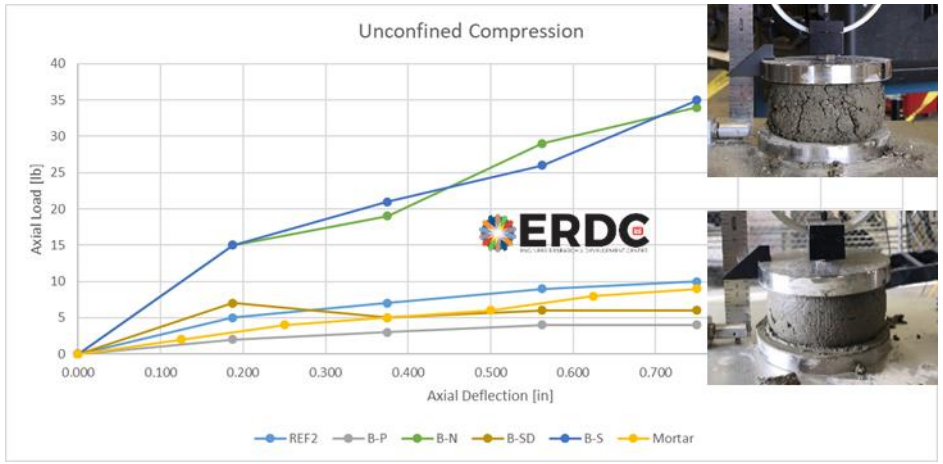
Materials Design and Quality Assurance

Materials Proportioning and Printability Testing

- Proportioning based on ACI 211
  - Trial batches are performed prior to printing
  - Developed using compression of cast samples (ASTM C39, C109)
- Rheometer
  - Lab and field solutions
  - **Cost limits widespread use**
- Unconfined compression
  - Can be performed in the lab or the field
  - Shape stability and print quality
  - Simple and easy to perform
  - Quantitative squeeze test
- Flow Test
  - Provides measurement of flow
  - Visual detection of segregation, and bleed water



Tests should be performed for very early ages: 0-2 hrs



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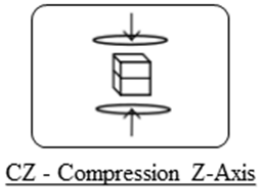
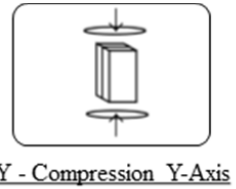
Materials Design and Quality Assurance

Materials Proportioning and Testing

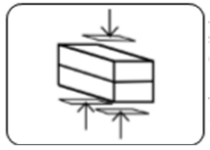
- **Full batch mixes for printing**
  - For new mixes a material should not be assumed printable
  - Mix adjustments required based on moisture content of aggregates
- **Print Stability Test**
  - Determine stability of print geometries using standard samples
  - Number of layers before collapse
  - Evaluation of failure mechanism (Elastic buckling, Plastic collapse)
- **Mechanical Testing of Hardened Printed specimens**
  - Printed material is not the same as cast materials
  - irregularities introduced
  - Compression, Flexural (Tested for anisotropy, 3 principal axes)
  - Interface tests for shear and tension
  - Samples should be representative of expected max time gap



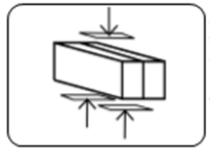
CZ - Compression Z-Axis



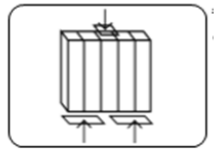
CY - Compression Y-Axis



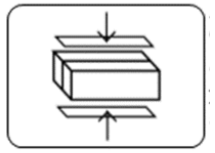
BX - Bending About X-Axis



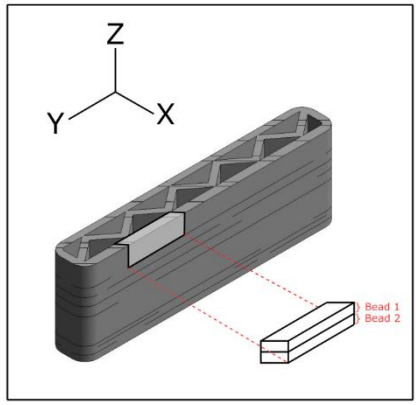
BZ - Bending About Z-Axis



IS - Interface Direct Shear



ST - Splitting Tension



Stidwell, Sam, Kreiger, Eric; Determination of Mechanical Properties Testing of Additively Constructed Concrete Based on Specimen Orientation, ASTM STP1636: Standards Development for Cement and Concrete for Use in AC

Materials Design and Quality Assurance

There is not enough data to support equivalency to current materials and design methods

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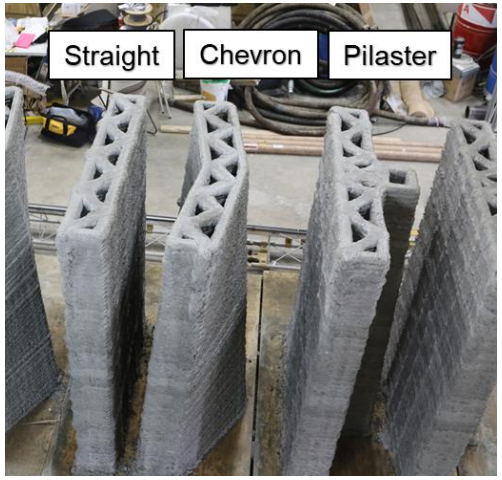
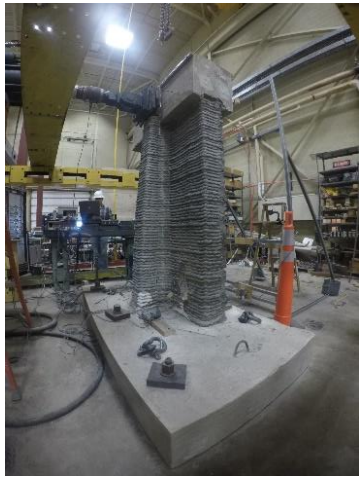
Structural Quality Assurance

Enhanced Barracks Hut (Champaign, IL)





- Designed using ACI 318
  - Assumed the printed portion had minimal contribution
- Tested 3 different wall geometries
- Tested in-plane shear and out-of-plane bending

Pedestrian Bridge (Camp Pendleton, CA)

- Designed using ACI 318
  - Did not account for layer effects in design
- First 3D printed bridge in the America's
- Broke the first 3D printed bridge in the Americas
- Performed monotonic 3 point bend test

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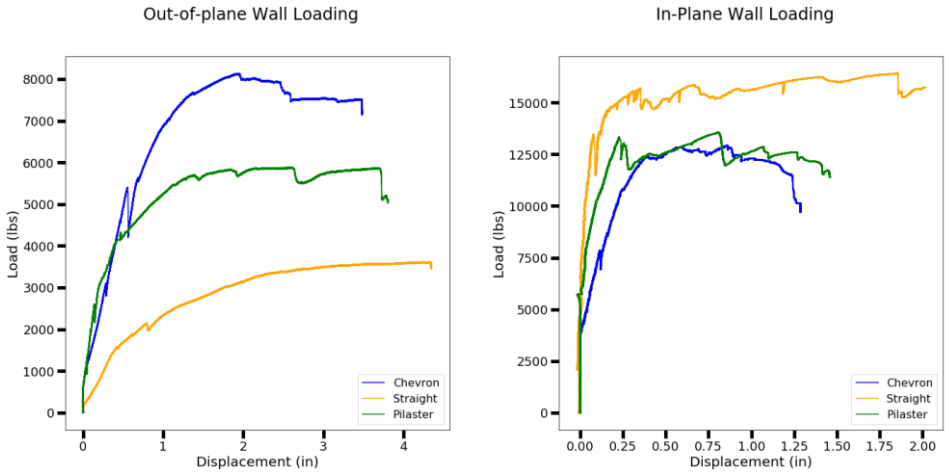
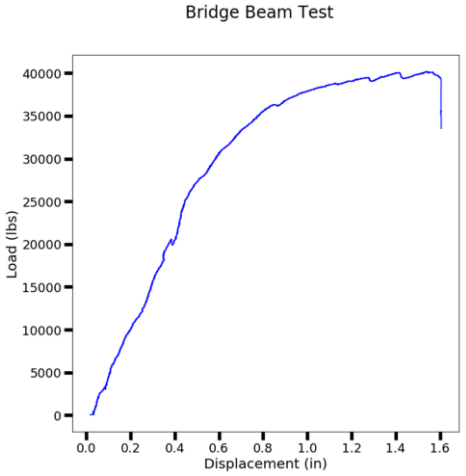
Structural Quality Assurance

Enhanced Barracks Hut (Champaign, IL)



- Out of plane design moment: 11 kip-ft (14.9 kNm)
- Out-of-plane test moment: 30 kip-ft (40.7 kNm)
  - Steel yielded prior to crushing
  - Failure at interface
- Chevron wall 2.5xs stronger than straight wall in out-of-plane
- Straight wall stronger than chevron or pilaster in in-plane loading: 15 kips (66 kN)

Pedestrian Bridge (Camp Pendleton, CA)

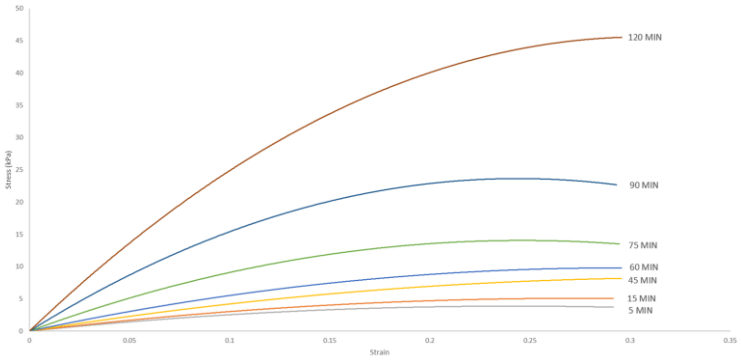


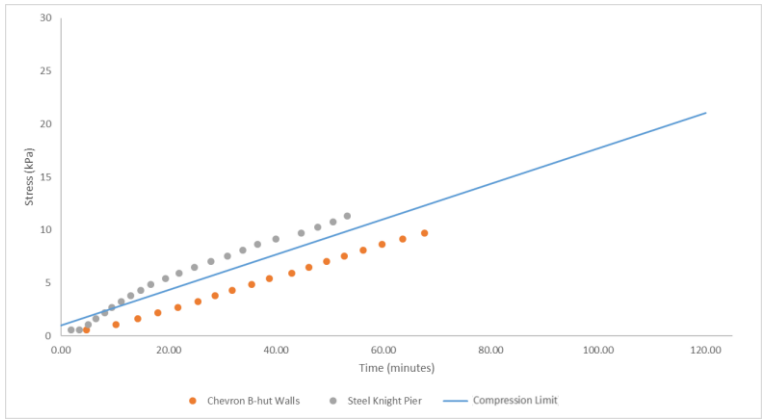
- Design Moment: 37.5 kip-ft (50.8 kNm)
- Design Shear: 7.5 kip (33.4 kN)
- Peak load: 40 kips (177.9 kN)
- Test Moment: 50 kip-ft (67.8 kNm)
- Test Shear: 10 kip (44.5 kN)

Quality Control

QC during construction

- QC must be performed during component creation
  - Confirming materials are same as those tested
- Documenting stops, delays, times to complete layers
  - Compare to QA very early age tests
- Perform fresh tests temp, air, unit weight
  - Following ASTM C31 and C192
  - Slump does not provide value
- Perform UC and flow, and rheology (if available)
- Print stability should be addressed in structural design
  - A stability test is recommended prior to printing



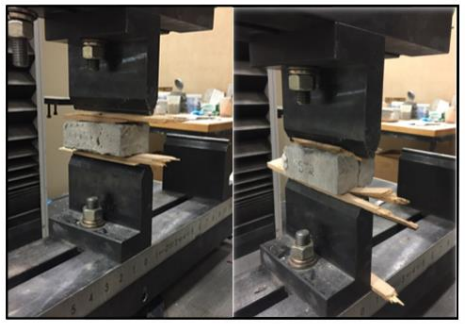


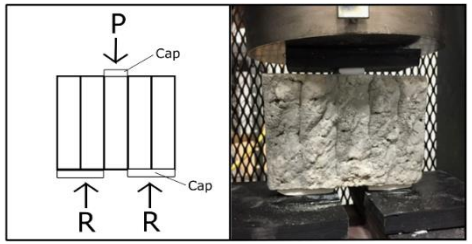
Diggs-McGee, B., Kreiger, E.; Using Isolated Temporal Analysis to Aid in the Assessment of Structural Element Quality for Additive Construction, ASTM STP1636: Standards Development for Cement and Concrete for Use in AC

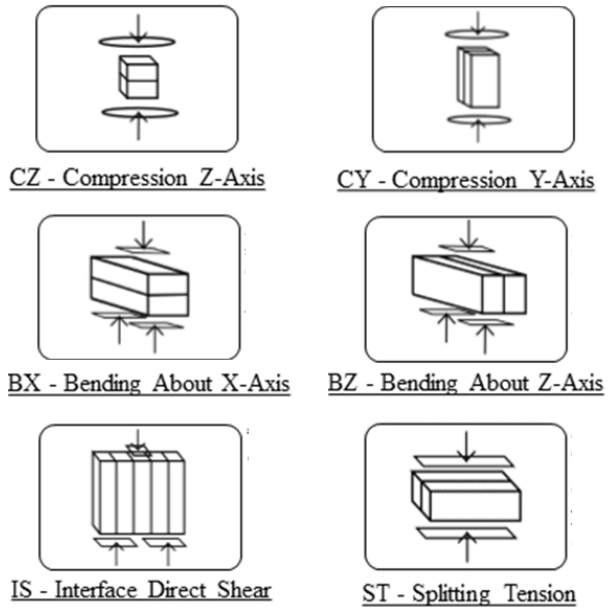
Quality Control

QC following construction

- QC of hardened printed elements
  - Sample Extraction Element adjacent to print
  - Confirming materials are same as those tested
  - Compression, flexural, interface
  - Tested for anisotropy - 3 principle axes
- Test 1 day, 3 day, 7 day, 28 day
- Compressive strength (Printed March 24th 2021)
  - Cast cube (28 day): 7817 psi (53.9 MPa)
  - Printed CZ (28 day): 5964 psi (41.1 MPa)
  - Printed CY (28 day): 5281 psi (36.4 MPa)
  - Printed strength can be 75% of cast strength
  - In agreement with other research (Ma et al 2018, Wolfs et al 2019, Panda et al 2017, Sanjayan et al 2018).







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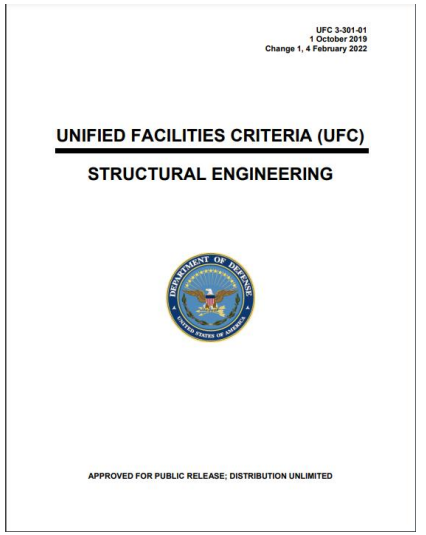
Materials Design and Quality Assurance


UFC 3-301-01
1 October 2019
Change 1, 4 February 2022

UNIFIED FACILITIES CRITERIA (UFC)

STRUCTURAL ENGINEERING

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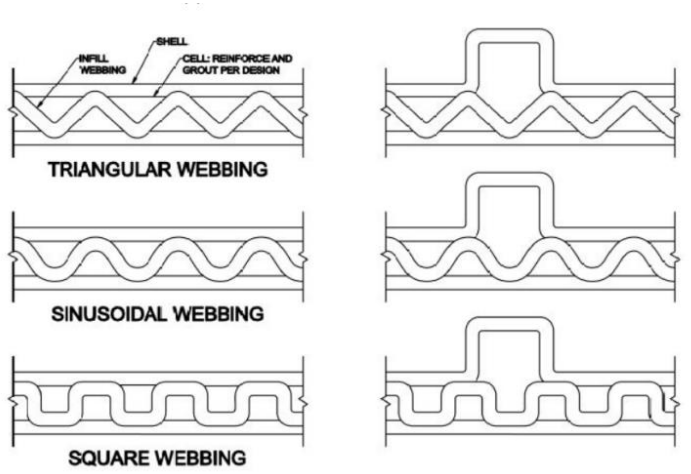
This work and the research of others led to the development of UFC 3-301-01 Section 2-7.2

- Provides structural design limitations for the technology
- Expands allowable structural geometry to walls with infill webbing and buttresses
- Required testing builds on the ICC ES AC 509 evaluation method
- Allows for the use of Additive Construction (3D Printing construction) in US DOD facilities.
- Testing and designs to be reviewed by my team as the Tri-Service SMEs



\1\2-7.2 **Section 1903 – SPECIFICATIONS FOR TESTS AND MATERIALS.**

1903.5 – Additively Constructed Concrete (3D Printed Concrete) [Addition]

Pursuant to UFC 1-200-01 Section 104.11, Concrete produced using additive construction, hereafter referred to as Additively Constructed Concrete (ACC), is allowed as an alternative material, design, and method of construction when adhering to the following requirements and when approved in writing by the AHJ.

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Closing Remarks

- Don’t be afraid to fail now in order to prevent failures during or after construction
- Understanding what tests are required for validation starts with design.
- Validation of AC through the use of alternative materials and methods sections is required.
  - IBC 104.11, IRC 104.11, UFC 1-200-01 104.11, AASHTO Section 1.1
- The development of new standards and guidance is required prior to code acceptance due to anisotropy, stress concentrations, and interface weakness that can occur.
- Validation, QA, of materials and structures required as there is no established design standard or formal training for this technology.
- Current methods may not go far enough, which is a concern for safety.
- Structural testing used to validate structural design or to provide guidance on design.
  - This should be required until design method is established
- Cast samples can be used for initial materials development, but are not recommended for
- For QA prior to construction and QC after construction mechanical test of printed sample should be performed
  - Printed strength for ACC has been shown to be less than cast strength.
- UFC 3-301-01 Section 2-7.2 provides designers with limitations and guidance

Contact Information:
Program Manager:
Ms. Megan Kreiger
megan.a.kreiger@usace.army.mil

Questions?

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