Wildfire risk mitigation in the WUI: From ignition-resistant to fire-resistant houses

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2nd Symposium on Wildfire-Induced Air Pollution Assessment and Mitigation
3/23/2022
Outline

➢ Introduction and Background

➢ Research Updates on Earth Block Construction
  ❑ Advancements in Finite Element Modeling
  ❑ Use of Sugarcane Bagasse Fibers

➢ Preliminary Results on Wildfire Resilience

➢ Ongoing and Future Work

➢ Conclusions
Introduction (1)

- Earthen structures are structures built using mainly soil
- Most ancient and sustainable building technique (> 10,000 years old)
- 30%-50% of world’s population currently lives in earth-based dwellings
- Earthen structures are found all over the world

Cities and examples:
- City of Potosí in Bolivia (1600-2100 CE)
- Pueblo de Taos, NM, USA (1000-1450 CE)
- Great Mosque of Djenné in Mali (300 BCE)

Earth construction areas of the world (Source: CRATerre/ENSAG/Auroville)

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Introduction (2)

➢ Cob
➢ Rammed earth
➢ Adobe
➢ Modern earth blocks
   ❑ Compressed earth blocks (CEB)
   ❑ Stabilized earth blocks (SEB)
   ❑ Compressed and stabilized earth blocks (CSEB)

El Haj Yousif experimental school in Sudan (Adam, 2001)
Ereth house in Davis, CA, USA (1955)
Compressed and Stabilized Earth Blocks (CSEB)

Fabrication process of CSEBs

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Results from Previous Studies

<table>
<thead>
<tr>
<th>Items</th>
<th>ICSEB Mortarless</th>
<th>Mortared CSEB</th>
<th>Light-frame Wood</th>
<th>Bricks</th>
<th>Concrete Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material ($)</td>
<td>7,186</td>
<td>6,676</td>
<td>15,638</td>
<td>19,533</td>
<td>12,844</td>
</tr>
<tr>
<td>Labor ($)</td>
<td>20,593</td>
<td>34,674</td>
<td>13,068</td>
<td>27,625</td>
<td>20,255</td>
</tr>
<tr>
<td>Overhead ($)</td>
<td>11,112</td>
<td>16,540</td>
<td>12,264</td>
<td>19,840</td>
<td>13,882</td>
</tr>
<tr>
<td>Total wall cost ($)</td>
<td><strong>38,891</strong></td>
<td><strong>57,890</strong></td>
<td><strong>40,970</strong></td>
<td><strong>66,997</strong></td>
<td><strong>46,981</strong></td>
</tr>
</tbody>
</table>

Overhead costs include interest, overhead, profits, and safety. The total wall cost is the sum of material, labor, and overhead costs.
FE Micro-Modeling of Masonry (1)

Masonry units

Unit-mortar interface

Masonry units

Mortar

Masonry units

Mortar joint interface

Expanded units

Masonry units

Mortar joint interface

Expanded units

Detailed micro-model (DMM)

Simplified micro-model (SSM)

Block direct tensile cracking

Joint tensile cracking

Joint slipping

Block diagonal tensile cracking

Masonry crushing

Masonry failure modes
FE Micro-Modeling of Masonry (2)

Validation of FE Response (DMM)

In-plane Min. Principal Stress (MPa)

Max. Principal Plastic Strain (mm/mm)

Horizontal force (kN)

Horizontal displacement (mm)
FE Micro-Modeling of Masonry (3)

Masonry Shear Walls: Experimental & FE response

Percentage error in peak strength and initial stiffness
CSEB Masonry: FE responses

Comparison between experimental and FE responses for CSEB wallets

In-plane minimum principal stress

In-plane maximum principal plastic strain

Experimental crack patterns (MC Cuellar-Azcarate 2016)
Use of Sugarcane Bagasse Fibers (SBF) in CSEBs

- Sugarcane production in 2018: 746.8 million metric tons (MMT) in Brazil, 376.9 MMT in India, and 108.7 MMT in China
  - > 400 million metric tons of SBF.

- USA sugarcane production in 2017: 28.0 MMT, mostly in Florida, Louisiana, and Texas,
  - ~ 9 million metric tons of SBFs.

- Brittle behavior of CSEBs can be improved using fibers
SBF-Reinforced CSEBs: Flexure Test

Unreinforced earth block

SBF-reinforced earth block

Crack pattern in unreinforced earth block

Crack pattern in SBF-reinforced earth block
SBF- Reinforced CSEBs: Compression Test

Unreinforced earth block

SBF-reinforced earth block

Cement content

0% 6% 12%

Compressive strength (MPa)

0.0% 0.5% 1.0%

Compressive stress (MPa)

Vertical displacement [mm]

Earth block with 6% cement

SBF 0.0%  SBF 0.5%  SBF 1.0%
SBF- Reinforced CSEBs: Durability Test

Wetting and drying durability test

Wetting (5 h)

Scratching surface

Drying (41 h)

12 Cycles

<table>
<thead>
<tr>
<th>Cement content</th>
<th>Loss in mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% SBF</td>
<td>Total loss</td>
</tr>
<tr>
<td>0.5% SBF</td>
<td>6% cement</td>
</tr>
<tr>
<td>1.0% SBF</td>
<td>12% cement</td>
</tr>
</tbody>
</table>

Specimens after durability test:

- 0% SBF
- 0.5% SBF
- 1.0% SBF

Cement content:

- 0%
- 6%
- 12%
California Wildfires History & Statistics

Data sources:
1. Estimated acres burned and confirmed loss of life: https://www.fire.ca.gov/incidents/
3. Economic losses: https://www.ncdc.noaa.gov/billions/time-series/CA
Effect of Climate Change on Wildfire Hazard

- Rising global temperatures are increasing the severity of wildfires across the western United States (Westerling 2018: CEC Report No. CCCA4-CEC-2018-014)

Wildfire simulations for California’s fourth climate change assessment projecting changes in extreme wildfire events with a warming climate
Ignition Mechanisms
Ignition Mechanisms

➢ Direct contact with flames/surface fires
Ignition Mechanisms

➢ Heat radiation/crown fires
Ignition Mechanisms

➢ Ember attacks/firebrands
California Building Code for WUI (Ch. 7A)

- Fire Resistance Test Standards
  - **Exterior wall siding/sheathing**: 150-kW direct flame exposure for 10 minutes
  - **Exterior windows**: 150-kW direct flame exposure for 8 minutes
  - **Decking**: under-deck exposure to 80-kW intensity direct flame for 3 minutes.
  - **Roof**: comply with various requirements (for coverings, valleys, and gutters) of Chapter 7A and Chapter 15 of California Building Code
  - **Horizontal projection underside**: 300-kW direct flame exposure for 10 minutes
  - **Other ignition-resistant materials** (e.g., fire-retardant-treated wood): 30-minute ASTM E84 or UL 723 tests

- **Exterior Protection**

- **Defensible Space** (5’, 30’, 100’)

CSEB Construction: Fire Resistance

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Unburned
After 7h at 1800 °F

© Karin Higgins, UC Davis
## CSEB Materials

<table>
<thead>
<tr>
<th>Laboratory tests</th>
<th>Standards</th>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle-size analysis</td>
<td>ASTM D6913-04</td>
<td>Gravel (&gt;2 mm) (%)</td>
<td>&lt;1.00</td>
</tr>
<tr>
<td></td>
<td>D7928-16</td>
<td>Sand (2–0.063 mm) (%)</td>
<td>61.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silt (0.063–0.002 mm) (%)</td>
<td>27.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clay (&lt;0.002 mm) (%)</td>
<td>11.86</td>
</tr>
<tr>
<td>Atterberg limits</td>
<td>ASTM D4318-10</td>
<td>Liquid limit LL (%)</td>
<td>32.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plastic limit PL (%)</td>
<td>21.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plasticity index PI (%)</td>
<td>10.65</td>
</tr>
<tr>
<td>Soil compaction tests</td>
<td>ASTM D698-12</td>
<td>Optimum moisture content (%)</td>
<td>20.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum dry density (kg/m³)</td>
<td>1711.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specific gravity of soil (-)</td>
<td>2.59</td>
</tr>
</tbody>
</table>
CSEB High Temperature Test
CSEB Specimens After High Temperature Test

CSEB specimens (left to right): 24±2°C, 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C.
# CSEB Flexure Test Results

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Modulus of Rupture</th>
<th>Modulus of Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (MPa)</td>
<td>COV (%)</td>
</tr>
<tr>
<td>24±2 °C</td>
<td>0.392</td>
<td>35.7</td>
</tr>
<tr>
<td>200 °C</td>
<td>0.317</td>
<td>25.5</td>
</tr>
<tr>
<td>400 °C</td>
<td>0.285</td>
<td>29.2</td>
</tr>
<tr>
<td>600 °C</td>
<td>0.291</td>
<td>28.0</td>
</tr>
<tr>
<td>800 °C</td>
<td>0.221</td>
<td>33.4</td>
</tr>
<tr>
<td>1000 °C</td>
<td>0.183</td>
<td>36.9</td>
</tr>
</tbody>
</table>
CSEB Flexure Test Results

- Modulus of Rupture (MPa) vs. Temperature (°C)
- Modulus of Elasticity (MPa) vs. Temperature (°C)

![Image of a sample under test]
# CSEB Compression Test Results

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Wet Compressive Strength</th>
<th>Modulus of Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (MPa)</td>
<td>COV (%)</td>
</tr>
<tr>
<td>24±2 °C</td>
<td>2.654</td>
<td>13.9</td>
</tr>
<tr>
<td>200 °C</td>
<td>3.120</td>
<td>42.6</td>
</tr>
<tr>
<td>400 °C</td>
<td>3.608</td>
<td>45.5</td>
</tr>
<tr>
<td>600 °C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>800 °C</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1000 °C</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Complete experimental testing under uniform heating.
Experimental testing under gradient temperature (ASTM E119).
Thermal properties (energy savings + wildfire indoor temperature).
Evaluation of emissions under wildfire conditions (individual house and community level).
Conclusions

➢ Earthen masonry represents an affordable, safe, and sustainable technique for construction of houses and low-rise buildings

➢ Finite element modeling using detailed micro-models is an accurate tool to predict mechanical behavior

➢ Natural fibers can be effectively used to improve the ductility

➢ Research is ongoing to develop an affordable fire-resistant construction technique based on CSEBs

➢ Earthen masonry shows great potential to address climate change and equitable economic development

➢ Future research will focus on wildfire resilience and mitigation of wildfire smoke emissions
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Thank you Questions?

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