Earth block construction: a sustainable housing solution for the wildland-urban interface (WUI)

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Outline

- Introduction
- Traditional Earthen Structures
- Earthen Construction: Advantages and Challenges
- Compressed and Stabilized Earth Block (CSEB) Construction
- Feasibility of Earthen Houses
- Wildfire Performance Assessment of CSEBs
Introduction

- Earthen structures built using mainly soil
- Very ancient techniques
- Several economic and sustainability advantages over more modern techniques
- A few significant challenges, particularly for non-engineered earthen structures
- Modern earthen construction techniques developed to address these issues, e.g., earth block construction
- Current research at UC Davis extending the use of earth block construction for fireproof buildings in the WUI
Traditional Earthen Structures (1)

- **Cob**
  - Sand, clay, water, some kind of fibrous or organic material (straw)
  - Soil mix is layered to build earth structures

- **Rammed earth**
  - Mixture of sand, clay, water, fiber, and gravel
  - Soil mix is compacted to build earth structures

- **Adobe/earth blocks**
  - Mixture of sand clay, water, and fibers is used to fabricate blocks
  - Earth structures are built with these blocks
Traditional Earthen Structures (2)

Great Mosque of Djenné in Mali
(300 BCE)

 Portions of the Great Wall built with rammed earth
(300 BCE - 1700 CE)

Pueblo de Taos in USA
(1100 CE – 1500 CE)

City of Potosí in Bolivia
(1600 CE – 2000 CE)

(Gandreau and Delboy 2012)
Earthen Construction: Advantages (1)

 Affordable and locally appropriate
   Soil is a widely available and inexpensive material
   This construction type is widely used around the world

 Indoor air quality and humidity efficient
   Earthen construction can keep the relative humidity of indoor air between 40% and 60%, which is most suitable for human health.

Earth construction areas of the world
(Auroville Earth Institute)
Earthen Construction: Advantages (2)

- Eco-efficient and sustainable
  - The embodied energy of earth buildings is significantly smaller than that of other conventional construction techniques

![Bar chart showing embodied carbon in different masonry materials](Morton et al. 2005)

- Very good isolation properties
  - High R-values, > 30% in HVAC energy savings
Earthen Construction: Advantages (3)

- Good hazard resistance
  - Hurricane resistance
  - Tornado resistance
  - Seismic resistance
  - Non-combustible

Masonry strength demand curves: (a) hurricane effects; and (b) tornado effects (Matta et al. 2015)

Structural detail for seismic-resistant reinforced earth block construction

Windborne debris impact resistance of earth block walls (Cuéllar-Azcárate MC 2016)
Earthen Construction: Challenges

- High variability of soil properties
- Poor durability against wet climates
- Britteness
- Widespread perception as a substandard choice
- Typically not thought in structural engineering curricula

The Ricola Herb Centre in Laufen (Basel), Switzerland

Childcare facility in Glendale, California
Compressed and Stabilized Earth Block (CSEB) Construction

- Masonry built using earth block fabricated by mechanically compressing a chemically stabilized soil mixture
Feasibility of Earthen Houses

- Focus on US Gulf Coast region (wet and humid climate)
- Motivation: need for affordable hurricane-resistant housing
  - 386,000 low-income households in Louisiana need affordable housing (U.S. Department of Housing and Urban Development in 2010)
- Challenges: poor soil quality, hot and wet climate, high wind loads, and cost
- Need for culturally-appropriate solutions
- Investigation performed for:
  - Structural feasibility
  - Architectural feasibility
  - Economic feasibility

(Kumar et al. 2018)
Hurricane Wind Resistance Study

- Strength demand curves developed by Matta et al. (2015)
- Characteristic masonry strength as per Eurocode 6 (CEDN 2005)
  - M09 - CSEB with 09% cement and respective mortar
  - M12 - CSEB with 12% cement and respective mortar

Schematic representation of wind pressures on MWFRS (Matta et al. 2015)

CSEB masonry strength demand curves for hurricane
Durability Study of CSEB Wall

**Mechanical properties of CBEBS before construction and after demolition of the wall**

<table>
<thead>
<tr>
<th>Tested specimens</th>
<th>MOR</th>
<th>$f_{bd}$</th>
<th>MOE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average (MPa)</td>
<td>Average (MPa)</td>
<td>Average (MPa)</td>
</tr>
<tr>
<td></td>
<td>COV (%)</td>
<td>COV (%)</td>
<td>COV (%)</td>
</tr>
<tr>
<td>CSEB (initial)</td>
<td>0.57</td>
<td>1.38</td>
<td>31.22</td>
</tr>
<tr>
<td></td>
<td>11.28</td>
<td>6.40</td>
<td>16.98</td>
</tr>
<tr>
<td>CSEB (protected)</td>
<td>0.64</td>
<td>1.79</td>
<td>55.61</td>
</tr>
<tr>
<td></td>
<td>22.68</td>
<td>5.55</td>
<td>20.21</td>
</tr>
<tr>
<td>CSEB (unprotected)</td>
<td>0.37</td>
<td>1.50</td>
<td>44.78</td>
</tr>
<tr>
<td></td>
<td>21.82</td>
<td>13.80</td>
<td>26.82</td>
</tr>
</tbody>
</table>

*MOR* = modulus of rupture; $f_{bd}$ = dry compressive strength; *MOE* = modulus of elasticity
## Cost comparison of different wall systems for reference shotgun prototypes house (1000 Square ft.)

<table>
<thead>
<tr>
<th>Items</th>
<th>Mortarless ICSEB</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 ($)</td>
<td>11,112</td>
<td>16,540</td>
<td>12,264</td>
<td>19,840</td>
<td>13,882</td>
</tr>
<tr>
<td><strong>Total wall cost ($)</strong></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>
<tr>
<td>Other assemblies ($)</td>
<td>65,110</td>
<td>65,110</td>
<td>65,110</td>
<td>65,110</td>
<td>65,110</td>
</tr>
<tr>
<td><strong>Total cost of house ($)</strong></td>
<td><strong>104,001</strong></td>
<td><strong>123,000</strong></td>
<td><strong>106,080</strong></td>
<td><strong>132,107</strong></td>
<td><strong>112,091</strong></td>
</tr>
<tr>
<td>Wall cost ratio (wcr)</td>
<td>1.00</td>
<td>1.49</td>
<td>1.05</td>
<td>1.72</td>
<td>1.21</td>
</tr>
<tr>
<td>House cost ratio (hcr)</td>
<td><strong>1.00</strong></td>
<td><strong>1.18</strong></td>
<td><strong>1.02</strong></td>
<td><strong>1.27</strong></td>
<td><strong>1.08</strong></td>
</tr>
</tbody>
</table>

- RS Means (2014, 2015) is used for the cost estimation
Wildfire Performance Assessment of CSEBs (1)

- 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 4th Climate Change Assessment projecting changes in extreme wildfire events under a warming climate
Wildfire Performance Assessment of CSEBs (2)

<table>
<thead>
<tr>
<th>State</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arizona</td>
<td>2,143,760</td>
<td>9,590</td>
<td>36,811</td>
<td>34,491</td>
</tr>
<tr>
<td>California</td>
<td>8,896,509</td>
<td>138,821</td>
<td>405,715</td>
<td>240,580</td>
</tr>
<tr>
<td>Colorado</td>
<td>1,674,723</td>
<td>33,461</td>
<td>91,026</td>
<td>113,002</td>
</tr>
<tr>
<td>Idaho</td>
<td>531,676</td>
<td>10,752</td>
<td>31,195</td>
<td>37,624</td>
</tr>
<tr>
<td>Montana</td>
<td>304,960</td>
<td>9,820</td>
<td>24,147</td>
<td>28,955</td>
</tr>
<tr>
<td>New Mexico</td>
<td>553,918</td>
<td>9,287</td>
<td>42,843</td>
<td>38,101</td>
</tr>
<tr>
<td>Nevada</td>
<td>939,019</td>
<td>1,104</td>
<td>7,998</td>
<td>6,989</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>1,310,426</td>
<td>284</td>
<td>383</td>
<td>172</td>
</tr>
<tr>
<td>Oregon</td>
<td>1,191,803</td>
<td>21,642</td>
<td>57,083</td>
<td>74,703</td>
</tr>
<tr>
<td>Texas</td>
<td>7,836,840</td>
<td>73,957</td>
<td>195,366</td>
<td>174,038</td>
</tr>
<tr>
<td>Utah</td>
<td>779,926</td>
<td>8,969</td>
<td>13,863</td>
<td>3,563</td>
</tr>
<tr>
<td>Washington</td>
<td>2,359,166</td>
<td>7,690</td>
<td>15,510</td>
<td>18,508</td>
</tr>
<tr>
<td>Wyoming</td>
<td>193,790</td>
<td>1,461</td>
<td>2,683</td>
<td>4,928</td>
</tr>
</tbody>
</table>
## Wildfire Performance Assessment of CSEBs (3)

### Reconstruction cost value of residence at risk by state (in $billions)

<table>
<thead>
<tr>
<th>State</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arizona</td>
<td>$448.74</td>
<td>$2.04</td>
<td>$7.95</td>
<td>$7.73</td>
</tr>
<tr>
<td>California</td>
<td>$3,381.07</td>
<td>$61.92</td>
<td>$189.00</td>
<td>$92.62</td>
</tr>
<tr>
<td>Colorado</td>
<td>$401.65</td>
<td>$9.55</td>
<td>$27.05</td>
<td>$33.66</td>
</tr>
<tr>
<td>Idaho</td>
<td>$122.70</td>
<td>$2.65</td>
<td>$7.52</td>
<td>$9.05</td>
</tr>
<tr>
<td>Montana</td>
<td>$65.55</td>
<td>$2.38</td>
<td>$5.94</td>
<td>$6.96</td>
</tr>
<tr>
<td>New Mexico</td>
<td>$116.66</td>
<td>$2.27</td>
<td>$10.66</td>
<td>$9.23</td>
</tr>
<tr>
<td>Nevada</td>
<td>$247.89</td>
<td>$0.39</td>
<td>$3.21</td>
<td>$2.92</td>
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<tr>
<td>Oklahoma</td>
<td>$249.75</td>
<td>$0.05</td>
<td>$0.06</td>
<td>$0.03</td>
</tr>
<tr>
<td>Oregon</td>
<td>$297.22</td>
<td>$5.46</td>
<td>$14.33</td>
<td>$18.64</td>
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<td>Texas</td>
<td>$1,717.30</td>
<td>$16.86</td>
<td>$42.97</td>
<td>$32.30</td>
</tr>
<tr>
<td>Utah</td>
<td>$187.62</td>
<td>$3.11</td>
<td>$5.02</td>
<td>$1.19</td>
</tr>
<tr>
<td>Washington</td>
<td>$608.26</td>
<td>$1.92</td>
<td>$4.00</td>
<td>$4.61</td>
</tr>
<tr>
<td>Wyoming</td>
<td>$43.60</td>
<td>$0.36</td>
<td>$0.67</td>
<td>$1.27</td>
</tr>
</tbody>
</table>
Wildfire Performance Assessment of CSEBs (4)

➢ Research Plan

- Characterize fire-induced changes in mechanical properties of CSEBs and CSEB masonry at different temperatures and temperature gradients
- Investigate the integration of other fire hardening systems (roof system and cover, vents, defensible space, etc.)
- Assess smoke toxicity of CSEBs houses compared to light-framed wooden houses

Design code-based fire time-temperature curves
Acknowledgements

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Thank you

Questions?

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