Experimental Study of Cement Mortar-Steel Fiber Reinforced Rammed Earth Wall

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- Numerical Analysis by FEM
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  - Wall Model Design
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1、Background

Snow and frozen rain disaster

2008, South China

Houses destroyed
/Severely damaged
2. Introduction of Rammed Earth

2.1 Examples of Rammed Earth Structure

- Tulou in Fujian
- Peifeng Pagoda, Qing Dynasty
- Old houses in Guangdong
2.2 Applications in Ancient China

- Straight Highway of Empire Qin, Jiangsu
- Jiaoshan emplacement, Jiangsu
- Tongwan Castle, Shaanxi, Northern and Southern Dynasties
- Coffin in the Tomb, Guangxi
2.3 Advantage of Rammed Earth Material

- Low-carbon property
- Convenient availability
- Good mechanical characteristic
- Economical
2.4 Composition of Rammed Earth

Lime  →  Rammed earth  →  Sand
Yellow Clay
3. Numerical Analysis

3.1 Similarity Principle

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Practical</th>
<th>Model</th>
<th>Similarity Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>3000mm</td>
<td>1500mm</td>
<td>$S_H = 1/2$</td>
</tr>
<tr>
<td>Width</td>
<td>4000mm</td>
<td>2000mm</td>
<td>$S_B = 1/2$</td>
</tr>
<tr>
<td>Thickness</td>
<td>240mm</td>
<td>240mm</td>
<td>$S_T = 1$</td>
</tr>
<tr>
<td>Ultimate Stress</td>
<td>$\sigma_p$</td>
<td>$\sigma_m$</td>
<td>$S_\sigma = 1$</td>
</tr>
<tr>
<td>Ultimate Capacity</td>
<td>$F_p$</td>
<td>$F_m$</td>
<td>$S_F = S_\sigma S_B S_T = 1/2$</td>
</tr>
</tbody>
</table>
### 3.2 Material Parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (mm)</th>
<th>Failure load (KN)</th>
<th>Compressive strengths (Kpa)</th>
<th>Mean value (Kpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>70</td>
<td>2.45</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>71</td>
<td>2.56</td>
<td>522</td>
<td>512.7</td>
</tr>
<tr>
<td>B3</td>
<td>71</td>
<td>2.53</td>
<td>516</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water content $w%$</th>
<th>Dry density $\rho_d$(kg/m$^3$)</th>
<th>Cohesion (Kpa)</th>
<th>Friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.5</td>
<td>1780</td>
<td>110.54</td>
<td>14.9</td>
</tr>
</tbody>
</table>
3.3 Constitutive Model

Least Square Method

\[
\frac{\sigma}{\sigma_0} = 3 \left( \frac{\varepsilon}{\varepsilon_0} \right)^4 - 8.78 \left( \frac{\varepsilon}{\varepsilon_0} \right)^3 + 7.33 \left( \frac{\varepsilon}{\varepsilon_0} \right)^2 - 0.62 \left( \frac{\varepsilon}{\varepsilon_0} \right)
\]
### 3.4 Numerical Analysis

#### Parameters of the wall models

<table>
<thead>
<tr>
<th>Model</th>
<th>Height×Width×Thickness</th>
<th>Window hole</th>
<th>Cement mortar in reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1500×2000×240mm³</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>M2</td>
<td>1500×2000×240mm³</td>
<td>400×500mm²</td>
<td>none</td>
</tr>
<tr>
<td>M3</td>
<td>1500×2000×240mm³</td>
<td>none</td>
<td>40mm(two sides)</td>
</tr>
<tr>
<td>M4</td>
<td>1500×2000×240mm³</td>
<td>400×500mm²</td>
<td>40mm(two sides)</td>
</tr>
</tbody>
</table>

![M1](image1.png) ![M4](image2.png)
3.5 Numerical Results and Analysis

Von Mises stress of the four models

M1

M2

M3

M4
3.6 Numerical Results and Analysis

Finite element analytical results before and after reinforcement

<table>
<thead>
<tr>
<th>Model description</th>
<th>Ultimate bearing capacity before reinforcement (Kpa)</th>
<th>Ultimate bearing capacity after reinforcement (Kpa)</th>
<th>Increasing percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single wall</td>
<td>375</td>
<td>878</td>
<td>134</td>
</tr>
<tr>
<td>Wall with window hole</td>
<td>260</td>
<td>567</td>
<td>117</td>
</tr>
</tbody>
</table>
4、Experimental study

4.1 Wall Model Designing

<table>
<thead>
<tr>
<th>Walls</th>
<th>Sand:Soil:Lime</th>
<th>Height<em>Width</em>Thickness</th>
<th>Window Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>3:1:0.6</td>
<td>1500<em>2000</em>240mm³</td>
<td>0</td>
</tr>
<tr>
<td>W2</td>
<td>3:1:0.6</td>
<td>1500<em>2000</em>240mm³</td>
<td>1</td>
</tr>
<tr>
<td>W3</td>
<td>3:1:1</td>
<td>1500<em>2000</em>240mm³</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: The proportion in the table is measured in mass

General configuration of the experimental device
4.2 Loading System
4.3 Data Collection

Dial gauges

Diagram showing force sensor, hydraulic jack, H-steel, and 10mm fine sand.
4.3 Data Collection

Strain rosettes
4.4 Cement Mortar-steel Fiber Reinforcement

Mortar layer

Tie bar

Steel web

Rammed earth wall
4.5 Failure Characteristics

**Before reinforcement:**

**For W1**
- Crack in the upper boundary
- Crack grows rapidly

**For W2, W3**
- Cracks on both sides of the upper corner
- Separation from the frame
4.5 Failure Characteristics

**After reinforcement:**

Cohesive failure of the rammed earth wall

*Separation to the original wall*
4.6 Strain and Deformation Analysis

Distribution of Dial Gauges

Loading-Deformation Curve of W3
4.6 Strain and Deformation Analysis

Distribution of Strain Rosettes

Loading-Strain Curve of W2
### 4.7 Test Results

<table>
<thead>
<tr>
<th>Walls</th>
<th>Cracking load (kN)</th>
<th>Ultimate bearing capacity (kN)</th>
<th>Raising in ultimate bearing capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>30</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>W1’</td>
<td>38</td>
<td>112</td>
<td>373%</td>
</tr>
<tr>
<td>W2</td>
<td>13</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>W2’</td>
<td>80</td>
<td>110</td>
<td>306%</td>
</tr>
<tr>
<td>W3</td>
<td>55</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>W3’</td>
<td>69</td>
<td>94</td>
<td>104%</td>
</tr>
</tbody>
</table>

![Bar chart showing comparison of cracking load and ultimate bearing capacity before and after reinforcement for W1, W2, and W3. The chart indicates a significant increase in bearing capacity after reinforcement, with percentages ranging from 104% to 373%.](image-url)
5. Conclusions

◆ Cement mortar-steel fiber reinforcement is effective to improve the ultimate bearing capacity of rammed earth wall.
◆ Lime helps to improve the strength of rammed earth wall.
◆ Boundary conditions affects the final results on the ultimate bearing capacity of the model.
◆ The separation of mortar layer from the original wall is due to rammed earth cohesive failure.
◆ The FEM results are expected to compare with the test results of the corresponding scaled model, and further studies are expected.
Thank you!