The textile block system: seismic analysis and upgrading

A. P. Vargas & G. G. Schierle

USC School of Architecture, Los Angeles, CA, USA

Abstract

The textile block system is a unique structural system created by Frank Lloyd Wright in the early 1920s, before any seismic regulations existed in California. The first four houses, all located in California, have been deteriorating severely due to seismic and environmental effects. Previous research and interventions to preserve them have not been completely successful. It is therefore important to carry out an analysis of the seismic vulnerability of these structures, and explore ways of strengthening them to comply with current seismic requirements. This paper demonstrates that the textile block system can be upgraded to current structural standards for seismic safety based on the International Building Code, IBC 2003 and codes for historical structures, including the California Historical Building Code and the Federal Emergency Management Agency (FEMA).

The Freeman House is used as case study. The allowable stress design method (ASD) is used for the analysis. The paper also discusses procedures and construction methods to strengthen existing textile block structure. The methodology presented may be used for seismic upgrading of other historic structures as well.

Keywords: textile block, Frank Lloyd Wright, ASD, allowable stress, shear walls, base shear, seismic analysis, seismic upgrading.

1 Introduction

With the recognition of Frank Lloyd Wright as great architect and designation of many of his buildings as historical monuments, there has been increasing emphasis placed on the preservation and conservation of his masterpieces.

This paper aims to analyze and upgrade with an affordable and non-destructive method the Freeman House, designed by Frank Lloyd Wright in
1924, as a case study for testing the textile block structural system, and compare that system with those used in three other textile block system houses, the Millard, Storer and Ennis-Brown Houses.

Figure 1: Millard House/block detail, Pasadena, CA. Freeman House/block detail, Hollywood, CA. Photos Angela Paola Vargas, 2004.


1.1 The textile block – an overview

In order to be able to assess damage to the textile block houses and propose solutions for preservation, it is important to first thoroughly understand the original components and structure of the textile block system. After the Millard House, Frank Lloyd Wright set about developing a way of strengthening the system. An important feature of his original system was that the blocks are stacked on top of each other without a mortar setting bed. Therefore, he improved the system by adding a network of inter-block joints, filled with grout and steel reinforced rods, similar to adobe construction in strength and resistance.

The original block was a 16" x 16" concrete tile, with a 1 ½" diameter semicircular channel running along each of the four sides, such that when two blocks are joined side-by-side, a circular channel is created, through which a steel bar is
run. For the Freeman House each block is of the same pattern, Fig. 1, 3. The blocks were created by pouring concrete mixture into molds, enabling the repetition of form, and reflecting the mechanization trend of that period in America. The textile blocks are reinforced by manufactured steel rods, which were run through the circular channels between the concrete blocks. Mortar was then poured into the channels, to bond the steel bars with the blocks. The steel grid in essence functions as a lateral system to resist shear, rather than spanning the whole structure.

![Section A](image1)

![Lateral View](image2)

![Section B](image3)

Figure 3: Freeman House, block dimensions, CAD – drawing/photos – Angela Paola Vargas, 2004, interpretation from archives.

![Section A](image4)

![Face of Block](image5)

![Section B](image6)

Figure 4: Ennis-Brown residence, photos – Angela Paola Vargas – 2004.

The types of damage typically found can be grouped into the following categories, according to this report: Deterioration or crumbling, spalling and ring fractures, erosion or weathering, and seismic shear cracks.
1.2 The textile block system and building codes

The Freeman House was built in 1924 and it is currently listed in the National Register of Historic Places. Therefore, any changes or restorations must comply with current building codes such as the 1997 Uniform Building Code (in order to comply with the State of California and the City of Los Angeles), the Secretary of Interior’s Standards for Rehabilitation, and the State Historic Building Code.

This analysis uses the fundamental assumptions, formulae and design procedures for the Allowable Stress Design Method. This method was selected for the analysis of the Freeman House following the recommendations provided by the California Historical Building Code, title 24, part 8 for existing structures. It is a non-invasive method, which is ideal for the Freeman House, a historical monument and an eligible National Landmark. In addition to the ASD method, the IBC 2003 and the USGS outline specific guidelines and coefficients that are used for this analysis.

2 Seismic analysis of the textile block system

2.1 Seismic Examination of a selected area of the Original Freeman House – allowable stress design

There are three basic assumptions in the analysis of the original Freeman House. Firstly, it is assumed that the walls act as ordinary reinforced masonry, according to the IBC 2003. This masonry is weak in shear walls. Secondly it is necessity to define the character of a structure as belonging to a category established by the IBC, through definition of materials, ultimate strength or yield strength, and a factor of safety. Thirdly, the structure is composed of steel-reinforced blocks, but further reinforcing steel is necessary to provide the shear strength and ductility necessary to resist seismic forces.

2.1.1 Block analysis

In order to measure the overall dead load of the selected area of the Freeman House, the basis of the Allowable Stress Design method, it is necessary to calculate individual block weight, which has been found to be on average 85 pcf (pounds per cubic foot).
Table 1: Block weight calculation.

<table>
<thead>
<tr>
<th>Block Weight (volume)</th>
<th>85 pcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block Weight (area) psf</td>
<td>1.03 ft$^3$ x 85 pcf / 1.32 = 51.8 psf</td>
</tr>
<tr>
<td>Block Weight (area) psf</td>
<td>52 psf</td>
</tr>
</tbody>
</table>

2.1.2 Dead load calculation
The ASD method is based on dead load, as defined by codes. The total dead load of the original section of the Freeman House is required to compute the base shear, which in turn is used to define the distribution of forces per level.

Table 2: Dead load (DL).

<table>
<thead>
<tr>
<th>Roof DL</th>
<th>W = 97 k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Floor Level 1 DL</td>
<td>W = 118 k</td>
</tr>
<tr>
<td>Total Dead Load</td>
<td>$\sum W = 215$ k</td>
</tr>
</tbody>
</table>

2.1.3 Determining the Freeman House seismic factor using IBC tables and the USGS earthquake hazard parameters
In order to determine the seismic factor, the Design Spectral Acceleration ($S_{DS}$) for the building needs to be defined. The first step is to identify the site class, using the IBC tables for the Freeman House, the default category D is used. The USGS Earthquake Hazard Parameters, define for each site probabilistic spectral accelerations, defined as $S_S$ (for low-rise) and $S_I$ (for high-rise) structures.

USGS spectral accelerations for seismic design are based on 2% probability of exceeding (PE) in 50 years. Based on the spectral acceleration $S_S$, IBC defines Design Spectral Acceleration $S_{DS}$ and the seismic coefficient $C_S$ as

$$C_S = \frac{I}{S_{DS}/R}$$

where

$I$ = Importance factor  
$R$ = Reduction factor

The seismic coefficient $C_S$ used to compute base shear:

$$V = C_S W$$

where $W$ = dead load

The $S_{DS}$ graphs (Fig. 6) [8] provide a streamlined method to define $S_{DS}$.

The seismic parameters of the Freeman House are:

$S_S = 205\%$, as decimal $S_S = 2$

For site class D, $S_{DS} = 0.95$

Importance factor $I = 1$

Masonry response factor $R = 2$

Base shear coefficient $C_S = \frac{I}{S_{DS}/R} = 1(0.95)/2 = 0.45$. 

2.1.4 Base shear \( V \)
Base shear, the total lateral force at the building base is computed as follows:
Dead load \( W = 215 \text{ k} + 20 \text{ k} \) (estimate for seismic upgrades), \( W = 235 \text{ k} \)
Adjustments per IBC:
- Ordinary masonry factor = 1.5
- Existing building factor = 0.85

Base shear \( V \)
\[
V = C_s W (1.5) (0.85) = 0.48 (235 \text{ k}) (1.5) (0.85) = 144 \text{ k}
\]

2.1.5 Force and shear distribution per level
Force distribution per level is computed as
\[
F_X = C_{vx} V
\]
\[
C_{vx} = \sum_{i=1}^{n} w_i h_i^k
\]

Shear distribution per level is computed as
\[
V_X = \sum_{i=1}^{n} F_i
\]

Force and shear distribution per level are tabulated in table 3. Shear per floor area is tabulated in table 4.
Table 3: Force and shear distribution.

<table>
<thead>
<tr>
<th>Level</th>
<th>Wx</th>
<th>hx</th>
<th>Wxhx</th>
<th>Wxhx / \sum Wihi</th>
<th>Fx = V (Wxhx / \sum Wihi)</th>
<th>\frac{Vx}{\sum Fx}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>97k</td>
<td>18'</td>
<td>1,746k'</td>
<td>0.6</td>
<td>144k (0.6) = 86k</td>
<td>86k</td>
</tr>
<tr>
<td>Lower</td>
<td>118k</td>
<td>10'</td>
<td>1,180k'</td>
<td>0.4</td>
<td>144k (0.4) = 58k</td>
<td>144k</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>\sum Wihi = 2,926k'</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Shear per floor area (square foot).

<table>
<thead>
<tr>
<th>v = V/A</th>
<th>V Per Level</th>
<th>A</th>
<th>V/A</th>
<th>v (psf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>86k = 86,000 #</td>
<td>1204 sf</td>
<td>86,000/1,204</td>
<td>71 psf</td>
</tr>
<tr>
<td>Level 0</td>
<td>144k=144,000 #</td>
<td>1208 sf</td>
<td>144,000/1,208</td>
<td>119 psf</td>
</tr>
</tbody>
</table>

2.1.6 Rebar size and spacing

Rebar size and spacing are computed as follows:

- The walls are 8" thick, with one inch of hollow space. Therefore, for calculation purposes, they are assumed to be 7" thick. The original rebars are ineffective as reinforcement for the structure. The seismic upgrading assumes:
  - Grade 60 rebars with allowable stress of $F_s = 24000$ psi.
  - Masonry specified compressive strength of $f_m = 1500$ psi
  - Allowable masonry shear stress of $F_v = 24$ psi.
  - Number 4 rebars (0.5" diameter) cross section area $A_v = 0.2$ in$^2$.

Rebar spacing $S$ is defined by the following formula:

$$S = \frac{A_v F_s}{F_v b}$$

where $A_v$ is the rebar cross-section area, $F_s$ is allowable rebar stress, $F_v$ is allowable wall shear stress, and $b$ is wall thickness. The space required between bars is computed as:

$$S = (0.2) \left( \frac{24000}{24} \right) \left( \frac{7"}{28} \right) = 28"$$

Considering the 8" masonry modules the bar spacing used is $S = 16"$. 
2.1.7 Determining the required effective wall length per level
The following formula determines required length per level \( (d') \), which is based on the base shear per level, divided per the allowable shear stress \( F_v \) by the wall thickness \( b \).

\[
d' = \frac{V}{F_v b}
\]

Table 5: Required shear wall lengths.

<table>
<thead>
<tr>
<th>Level</th>
<th>Converting to feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>512&quot; / 12 = 43&quot;</td>
</tr>
<tr>
<td></td>
<td>( d' = 86,000#/24(7&quot;) ) ( L = d' + 8&quot; )</td>
</tr>
<tr>
<td></td>
<td>( d' = 144,000#/168 ) ( L = 144.66' ) Use ( L = 44' )</td>
</tr>
<tr>
<td></td>
<td>( d' = 857&quot; ) Use 33 modules of 16&quot; = 44' each way</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level 0</th>
<th>Converting to feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>857&quot; / 12 = 71'</td>
</tr>
<tr>
<td></td>
<td>( d' = 144,000#/24(7&quot;) ) ( L = d' + 8&quot; ) ( L = 71'+0.66&quot; )</td>
</tr>
<tr>
<td></td>
<td>( d' = 144,000#/168 ) ( L = 71'+0.66&quot; ) ( L = 72' )</td>
</tr>
<tr>
<td></td>
<td>( d' = 857&quot; ) Use 54 modulus of 16&quot; = 72' each way</td>
</tr>
</tbody>
</table>

References

