The textile block system: seismic analysis and upgrading

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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

WIT Transactions on The Built Environment, Vol 95,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/STR070601

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.

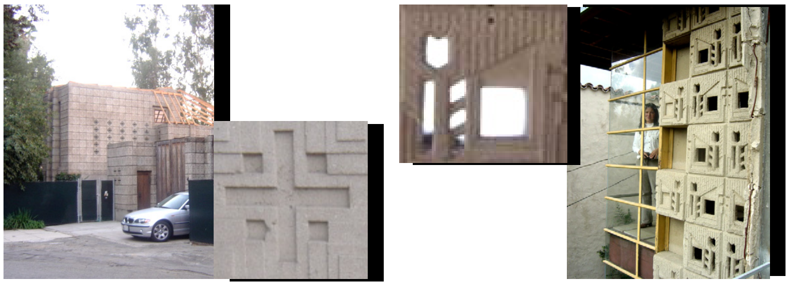


Figure 1: Millard House/block detail, Pasadena, CA. Freeman House/block detail, Hollywood, CA. Photos Angela Paola Vargas, 2004.

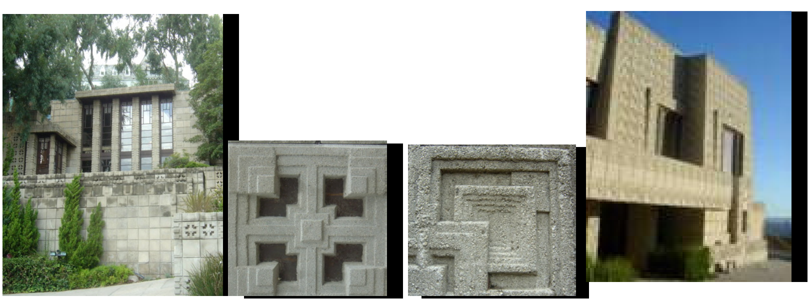


Figure 2: Storer House/block detail, Hollywood, CA. Ennis-Brown House/block detail, Hollywood, CA. Photos Angela Paola Vargas, 2004.

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 semi-circular 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.

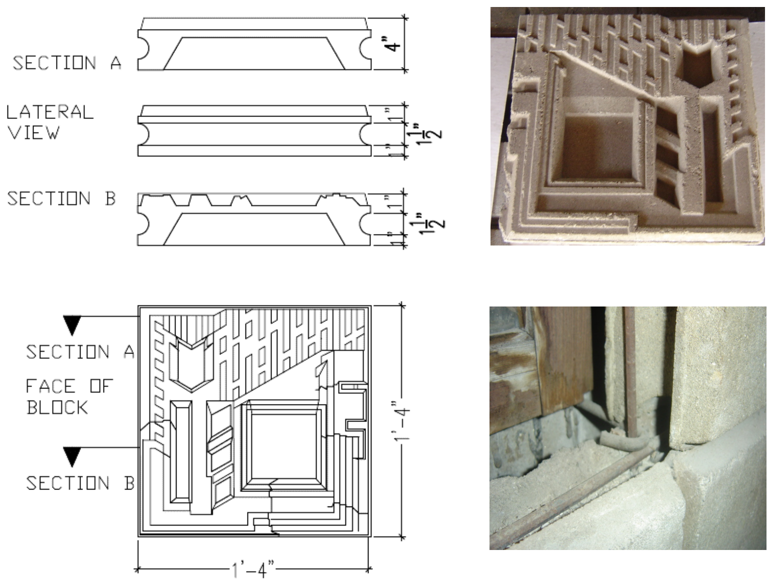


Figure 3: Freeman House, block dimensions, CAD – drawing/photos – Angela Paola Vargas, 2004, interpretation from archives.

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.

Figure 5: Typical damage, photos – Angela Paola Vargas – 2004.

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.

Block Weight (volume)	85 pcf
Block Weight (area) psf	$1.03 ft^3$ x 85 pcf / 1.32 = 51.8 psf
Block Weight (area) psf	52 psf

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).

Roof DL	W = 97 k
Ground Floor Level 1 DL	W = 118 k
Total Dead Load	$\underline{\sum W = 215\text{ k}}$

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_1 (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

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

where

I = Importance factor
R = Reduction factor

The seismic coefficient C_S used to compute base shear:

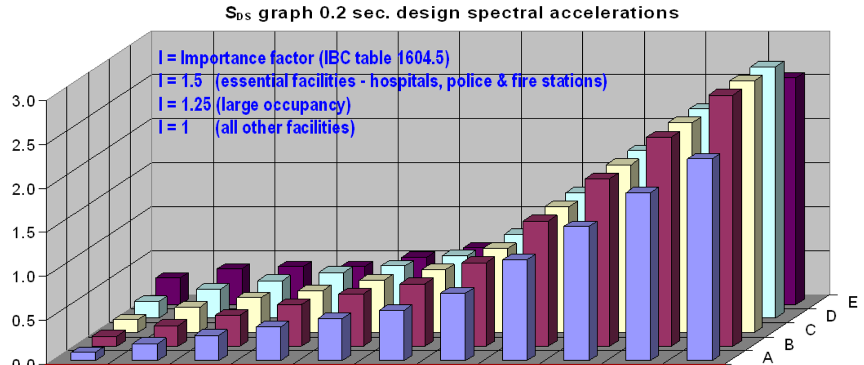
$$V = C_S W$$

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 $C_S = I\, S_{DS} / R = 1(0.95)/2 = 0.45$.



	0.25	0.5	0.75	1	1.25	1.5	2	3	4	5	6	← S_S from USGS
A	0.10	0.19	0.29	0.38	0.48	0.57	0.76	1.14	1.52	1.90	2.28	hard rock
B	0.12	0.24	0.36	0.48	0.60	0.71	0.95	1.43	1.90	2.38	2.86	rock
C	0.14	0.29	0.39	0.48	0.60	0.71	0.95	1.43	1.90	2.38	2.86	dense soil
D	0.19	0.33	0.43	0.52	0.60	0.71	0.95	1.43	1.90	2.38	2.86	stiff soil
E	0.30	0.40	0.43	0.43	0.54	0.64	0.86	1.29	1.71	2.14	2.57	soft soil

S_{DS}

Figure 6: S_{DS} graphs. (Site classes A-E, default site class D used.)

2.1.4 Base shear V

Base shear, the total lateral force at the building base is computed as follows:
Dead load W= 215 k + 20 k (estimate for seismic upgrades), W = 215+20 = 235k
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 computes as

$$F_X = C_{vx} V$$

$$C_{VX} = w_x h_x^k / \sum_{i=1}^{n} w_i h_i^k$$

Shear distribution per level is computes as

$$V_X = \sum_{i=x}^{n} F_i$$

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.

Force and Shear Distribution per Level						
Level	Wx	hx	Wxhx	Wxhx ∑ Wihi	Fx = V (Wxhx / ∑ Wihi)	Vx= ∑Fx
Main (Level 1)	97k	18'	1,746k'	0.6	144k (0.6)=86k	86k
Lower Level 0)	118k	10'	1,180k'	0.4	144k (0.4)=58k	144k
			∑Wihi= 2,926k'			

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

Shear per Floor Area per Level				
v = V/A	V Per Level	A	V/A	v (psf)
Level 1	86k = 86,000 #	1204 sf	86,000/1,204	71 psf
Level 0	144k=144,000 #	1208 sf	144,000/1,208	119 psf

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 Fs =24000 psi.
- Masonry specified compressive strength of fm =1500 psi
- Allowable masonry shear stress of Fv =24 psi.
- Number 4 rebars (0.5" diameter) cross section area Av = 0.2 in^2.

Rebar spacing S is defined by the following formula:

$$S = Av\ Fs / (Fv\ b)$$

where Av is the rebar cross-section area, Fs is allowable rebar stress, Fv is allowable wall shear stress, and b is wall thickness. The space required between bars is computed as:

$$S = (0.2)\ (24000) / (24)\ (7'') = 28''$$

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 Fv by the wall thickness b.

Table 5: Required shear wall lengths.

Level 1	Converting to feet	
d' = V / (Fv b)	512" / 12 = 43"	
d'=86,000#/24) (7")	L=d+8"	
d'=86,000# / 168	L= 43.66'	Use L=44'
d'=512"	Use 33 modules of 16"= 44' each way	
Level 0	Converting to feet	
d' = V / (Fv b)	857" / 12 = 71'	
d'=144,000#/24(7")	L=d+8"	L=71'+0.66
d'=144,000# / 168	L=71'+0.66"	L=72'
d'=857"	Use 54 modulus of 16" = 72' each way	

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www.witpress.com, ISSN 1743-3509 (on-line)