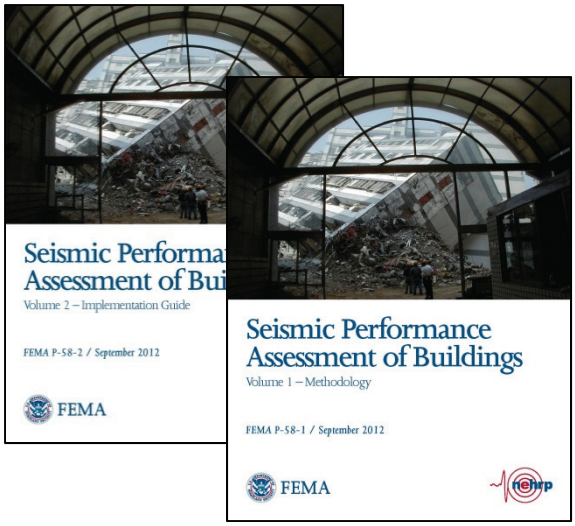

Background Document

FEMA P-58/BD-3.9.14

Fragility of Traction Elevators

Prepared by

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Submitted to

APPLIED TECHNOLOGY COUNCIL
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Prepared for

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U.S. Department of Homeland Security
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July 15, 2009

FEMA

nehrp

Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. Users of information in this document assume all liability arising from such use.

Notice

Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

Fragility of traction elevators

Keith Porter (07/15/2009)

Table 1. Summary results

Fragility, damage measures, and consequences for			
Component category:	D1014.010, Traction elevators, unknown installation D1014.011, Traction elevators installed 1973-1994 D1014.012, Traction elevators installed pre-1973		
Basic composition:	See Figure 1		
Units:	One elevator		
Demand parameter:	Maximum-direction peak ground acceleration		
Number of damage states:	17		
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☒ simultaneous		
Author and date:	K Porter 15 July 2009		
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:	Controller anchorage failed	Machine anchorage failed	Motor generator anchorage failed
Illustration:	Figure 2	Not available; observed in Olive View Hosp. elevs 3 & 4 after 1994 Northridge	Figure 3
Median demand (θ)[(1)]:	0.35		
Data dispersion (β_d)[(2)]	0.40		
Uncertainty (β_u)[(2)]	0.10		
Total dispersion (β)[(1)]:	0.40		
Probability[(1)]:	0.005*	0.06	0.17
Correlation:			
Repairs required:	Reinstall or replace controller	Reinstall w new snubbers	Reinstall w new snubbers
Possible consequences:			
Repair cost (Y/N/?):	Y	Y	Y
Death or injury (Y/N/?):	N	N	N
Inoperative facility (Y/N/?):	Y	Y	Y
Red tagging (Y/N/?)	N	N	N
Comments[(2)]:			

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) For methods A and B only, provide β_d and β_u and explain in the "comments" row any β_u value that differs from recommendations in Appendix C.

* This damage state was observed in other events, and so a token probability is included here.

	DS4	DS5	DS6
Description:	Governor anchorage failed	Rope guard failures	Rail distortion
Illustration:	Not available; observed in Olive View Hosp. elev. 4, Northridge earthquake	Not available; observed in Olive View Hosp. elevs. 5 & 6, Northridge earthquake	Figure 4
Median demand (θ)[1]:			
Data dispersion (β_r)[2]			
Uncertainty (β_u)[2]			
Total dispersion (β)[1]:			
Probability[1]:	0.02	0.04	0.79
Correlation:			
Repairs required:	Reinstall or replace	Reinstall or replace	Reinstall or replace
Possible consequences:			
Repair cost (Y/N/?):	Y	Y	Y
Death or injury (Y/N/?):	N	N	Y
Inoperative facility (Y/N/?):	Y	Y	Y
Red tagging (Y/N/?)	N	N	N
Comments[2]:			

	DS7	DS8	DS9
Description:	Intermediate bracket separate and spread	Counterweight bracket break or bend	Car bracket break or bend
Illustration:	Figure 5	Figure 6	Figure 8
Median demand (θ)[1]:			
Data dispersion (β_r)[2]			
Uncertainty (β_u)[2]			
Total dispersion (β)[1]:			
Probability[1]:	0.26	0.13	0.09
Correlation:			
Repairs required:	Replace bracket or tire rod	Replace bracket	Replace bracket
Possible consequences:			
Repair cost (Y/N/?):	Y	Y	Y
Death or injury (Y/N/?):	Y	Y	Y
Inoperative facility (Y/N/?):	Y	Y	Y
Red tagging (Y/N/?)	N	N	N
Comments[2]:			

	DS10	DS11	DS12
Description:	Car guide shoes damaged	Counterweight guide shoes damaged	Counterweight frame distortion
Illustration:	Not available. Damage to car rollers and guides was observed in LA County/USC Medical Center Pediatrics & Womens elevs 1-7 after Northridge earthquake	Figure 6	Figure 7
Median demand (θ)[1]:			
Data dispersion (β_r)[2]			
Uncertainty (β_u)[2]			
Total dispersion (β)[1]:			
Probability[1]:	0.32	0.34	0.26
Correlation:			
Repairs required:	Replace	Replace	Repair or replace counterweight frame
Possible consequences:			
Repair cost (Y/N/?):	Y	Y	Y
Death or injury (Y/N/?):	N	N	Y
Inoperative facility (Y/N/?):	Y	Y	Y
Red tagging (Y/N/?)	N	N	N
Comments[2]:			

	DS13	DS14	DS15
Description:	Cab stabilizers bent	Cab ceiling damaged	Cab walls damaged
Illustration:	Not available	Figure 9	Not available
Median demand (θ)[1]:			
Data dispersion (β_r)[2]			
Uncertainty (β_u)[2]			
Total dispersion (β)[1]:			
Probability[1]:	0.60	0.17	0.02
Correlation:			
Repairs required:	Repair or replace	Repair or replace	Repair or replace
Possible consequences:			
Repair cost (Y/N/?):	Y	Y	Y
Death or injury (Y/N/?):	N	Y	Y
Inoperative facility (Y/N/?):	Y	Y	Y
Red tagging (Y/N/?)	N	N	N
Comments[2]:			

	DS16	DS17
Description:	Cab doors damaged	Tail sheave dislodged and/or twisted
Illustration:	Not available	Not available
Median demand (θ)[(1)]:		
Data dispersion (β_r)[(2)]		
Uncertainty (β_u)[(2)]		
Total dispersion (β)[(1)]:		
Probability[(1)]:	0.11	0.005*
Correlation:		
Repairs required:	Repair or replace	Repair or replace
Possible consequences:		
Repair cost (Y/N/?):	Y	Y
Death or injury (Y/N/?):	N	N
Inoperative facility (Y/N/?):	Y	Y
Red tagging (Y/N/?)	N	N
Comments[(2)]:		

* This damage state observed in other events, so a token probability is included here.

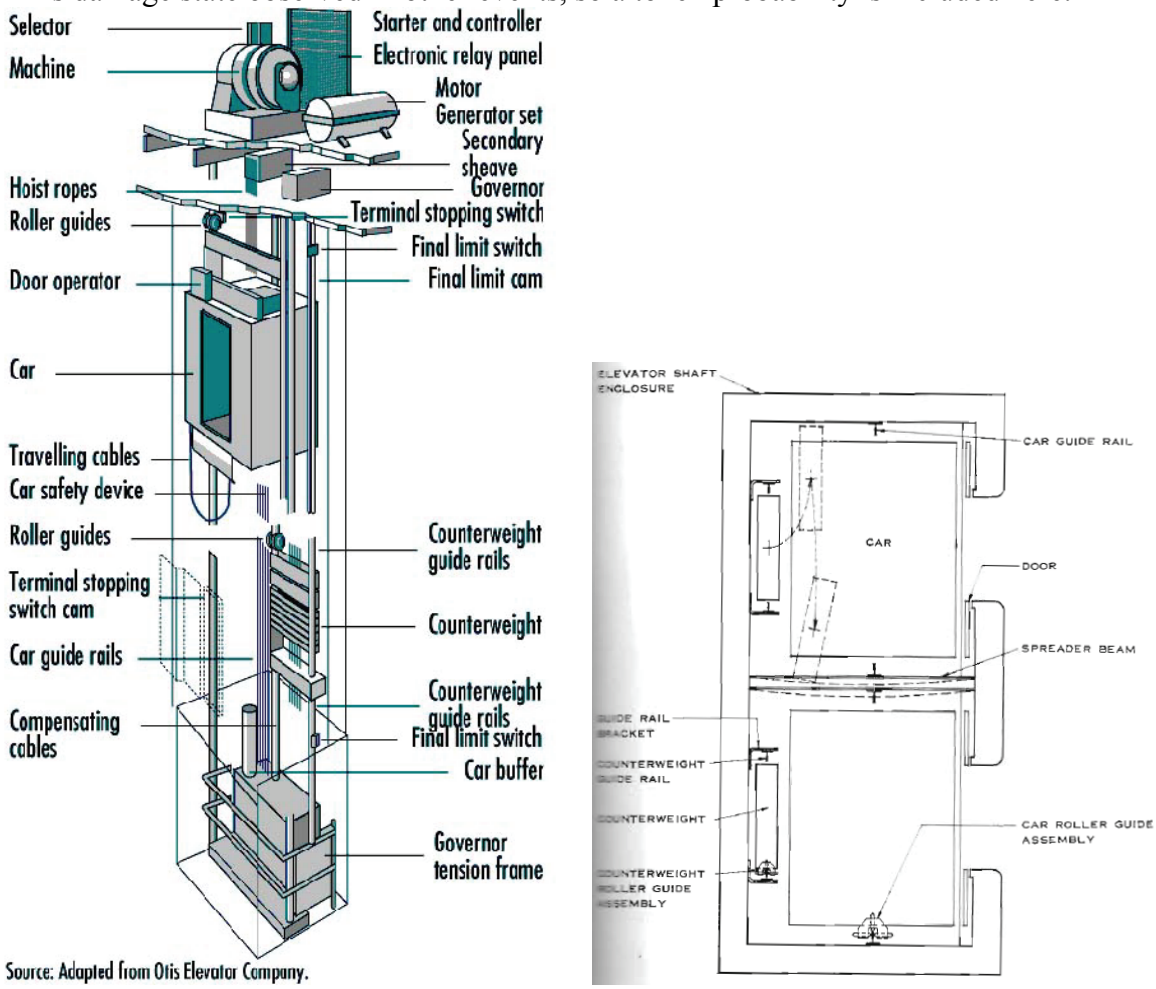


Figure 1. (a) Typical components of a traction elevator, and (b) horizontal section showing typical 2-car elevator shaft (Ayres et al. 1973)

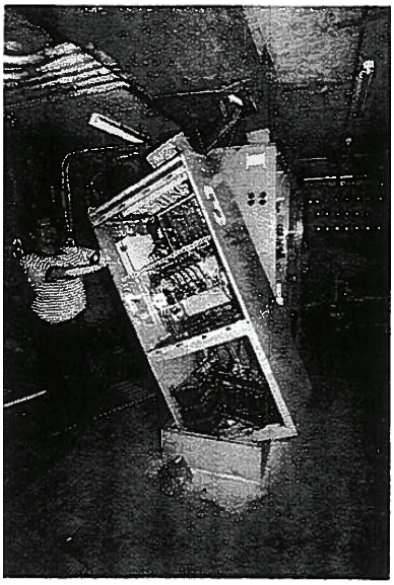
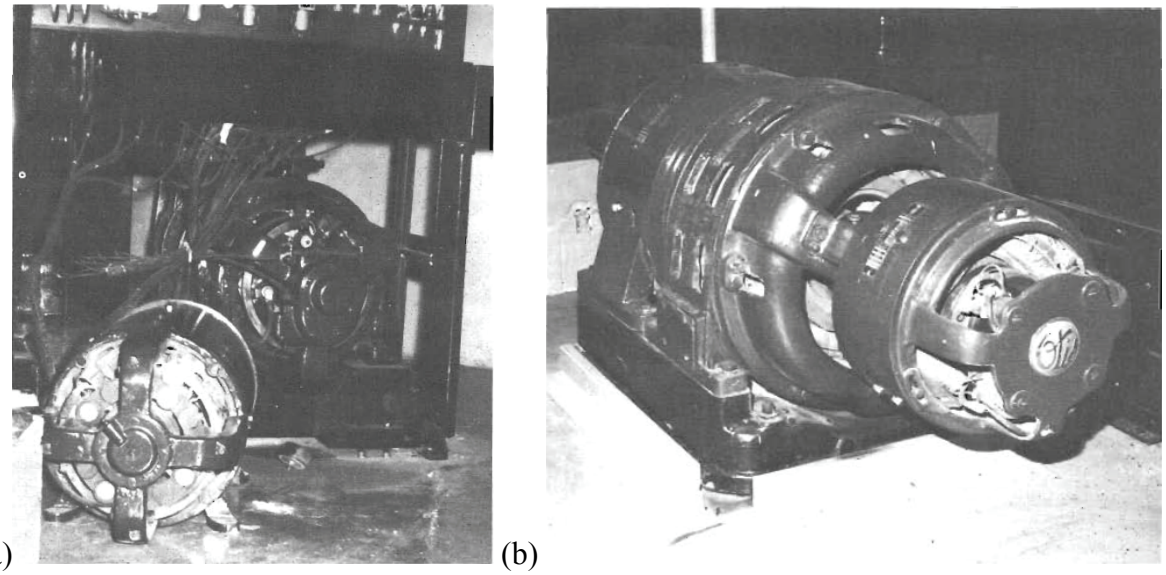


Figure 2. Damage state 1: controller panel anchorage failure observed in a large hotel after the 1993 Guam earthquake (Gates and McGavin 1998)



(a) (b)

Figure 3. Damage state 3: (a) motor generator thrown from its vibration isolators observed in the Alaska Native Hospital after the 1964 Alaska earthquake, and (b) remediation: motor generator constrained by neoprene-padded angle irons bolted to the floor (Ayres et al. 1973, photo by Don St Louis).

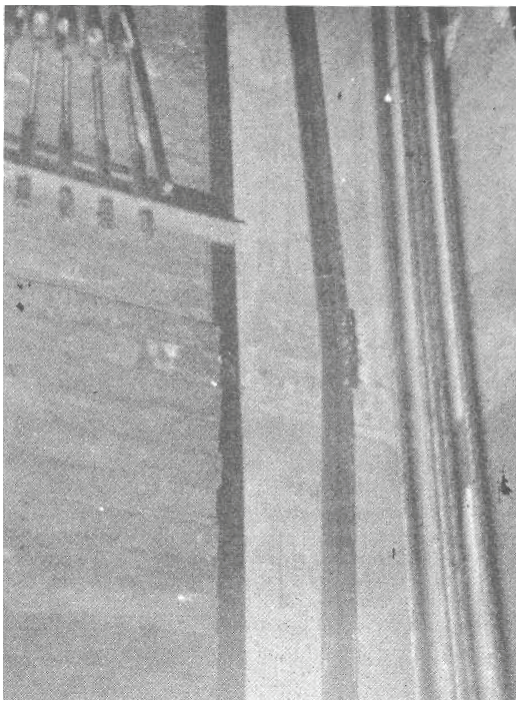


Figure 4. Damage state 6: bent counterweight guide rail observed in the Anchorage-Westward Hotel after the 1964 Alaska earthquake (Ayres et al. 1973, photo by Fred Hosel)

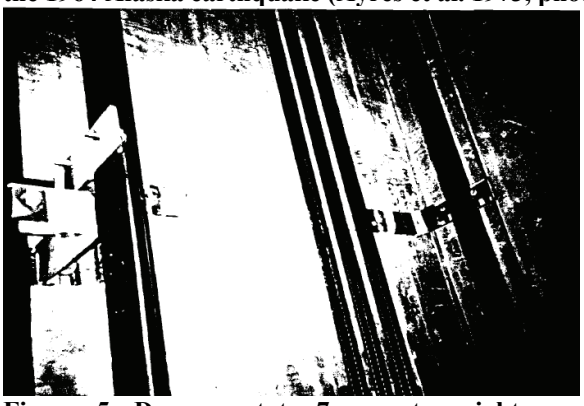


Figure 5. Damage state 7: counterweight spreader bracket observed after the 1994 Northridge earthquake in Valley Presbyterian Hospital. The 3/8-in bracket bent, allowing rail distortion (Finley et al. 1996).

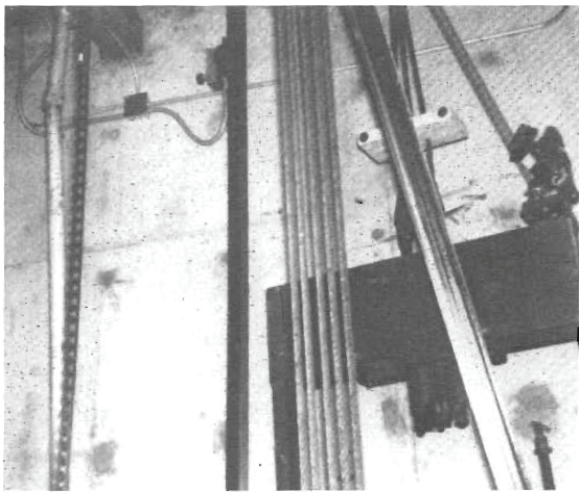


Figure 6. Damage states 8 and 11: roller guide assembly missing from upper left-hand corner of counterweight frame in Hill Building (DS11), observed after the 1964 Alaska earthquake. Right counterweight guide rail has become disconnected from the wall, visible in the foreground (Ayres et al. 1973, photo by Fred Hosel).

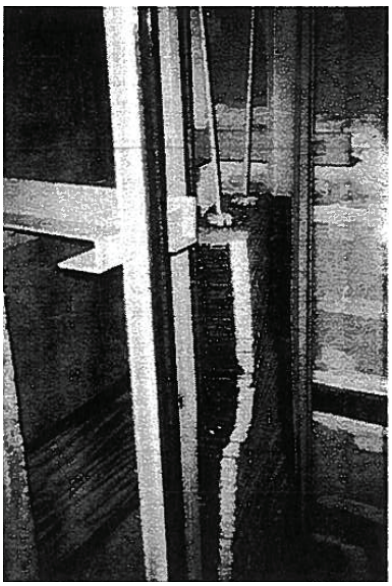


Figure 7. Damage state 12: distorted counterweight frame at the Olive View Hospital after the 1994 Northridge earthquake (Gates and McGavin 1998).

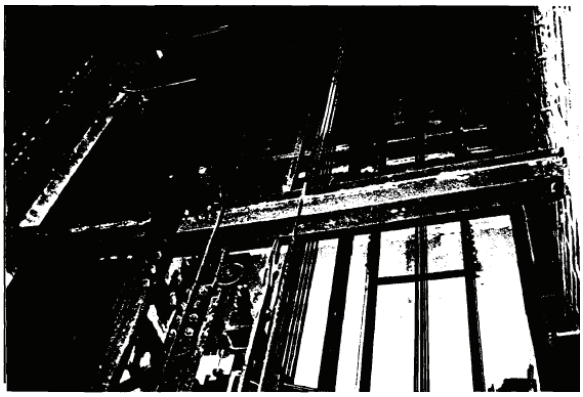


Figure 8. Damage state 9: in the Northridge Hospital Medical Center, 1967 Westinghouse elevators 1-4 all experienced damaged car rail brackets. Here, the spreader beam running horizontally through the photo is bent. The car rail guide running vertically through the photo in the left 1/3rd is attached to the beam and is bent with it. Repair was carried out by inserting shims between the bent spreader beam and the car rail bracket.

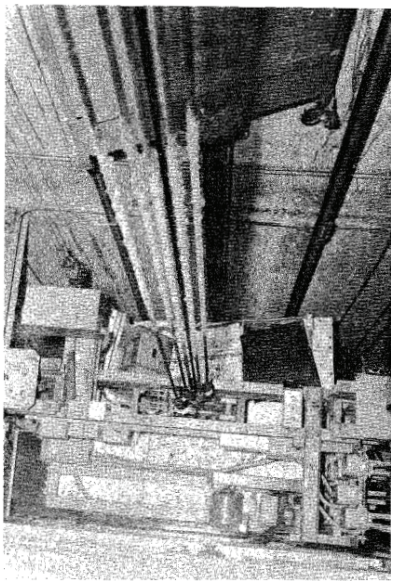
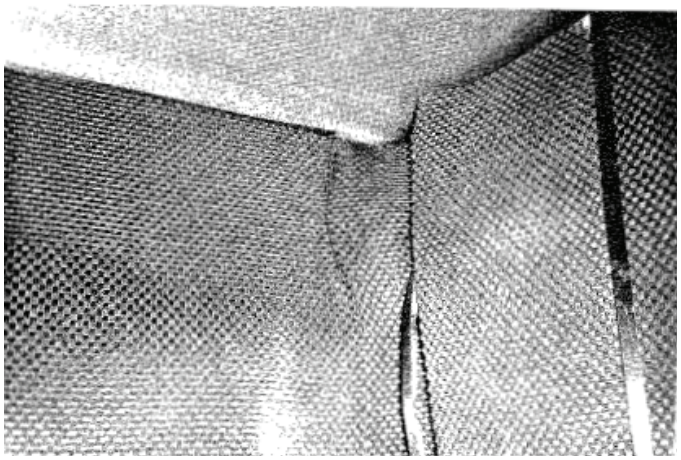
(a)  (b) 

Figure 9. Damage state 14: (a) derailed counterweight in the Union Oil Building struck the top of the elevator car in the 1971 San Fernando earthquake; (b) a view from the inside of the damaged car (Ayres and Sun 1973)

Table 2. Summary supporting information template

<table>
<tr><td colspan="2">Literature summary
See attached MS: “Seismic fragility of traction elevators.” Submitted to Earthquake Spectra Oct 2008, revised Apr 2009 to reflect FRP Dec 2008 comments, revised July 2009 to reflect newly acquired Loma Prieta data. In summary, Finley et al. (1996) provide detailed failure and success data for 93 traction elevators at 8 hospitals shaken with PGA > 0.25g in the 1994 Northridge earthquake. Hospitals exhibit per-site failure rates of 0.08 to 1.0. HKA (1992) provide similar (though less detailed) data about 22 elevators (of which 8 failed) at 4 hospitals after the Loma Prieta earthquake; these were shaken much less strongly, 0.09 to 0.2g. PGA is known for 2 of the hospitals from instruments on site, and estimated for the other two by HKA (1992) based on instruments 4 and 6 miles away. Naeim (1997) provides qualitative damage data for 6 buildings shaken with PGA ≤ 0.25g, with failure rates of 0 to perhaps 0.3 (“perhaps” because the damage is qualitatively described, and the present author somewhat arbitrarily assigned failure rates are to the damage descriptions). Damage states of interest include failure of equipment anchorage, damage to car guide shoes, cab stabilizers, or cab interior. Other damage states examined by Finley et al. (1996) are ignored, including loss of building power, damage to the hoistway walls or sprinkler pipes, and snagged ropes and traveling cables. This last is excluded because (a) it is easily cleared, and (b) Finley’s text disagrees with the elevator-by-elevator record of this failure mode. E.g., the latter indicates failure in every elevator at Cedars Sinai while the text says “snagged governor cables in about half the elevators.” Note that Finley et al. (1996) believed that elevator manufacturers and installation dates might be material to understanding damage, as did Schiff (2006), so these data are repeated here for later reference.</td></tr>
<tr><td>Number of specimens tested:</td><td>115</td></tr>
<tr><td>Construction quality:</td><td>□ exceeds □ meets □ does not meet requirements of:
<u>Some meet, some not, 1972 Hospital Seismic Safety Act</u></td></tr>
<tr><td>Seismic installation conditions:</td><td>Counterweight rail weight varies, some 8 plf, some 15;
Counterweight bracket spacing varies, 6-15 ft;
Car rail generally 15 plf. These stats reflect Finley et al. (1996) hospital observations only.</td></tr>
<tr><td>Loading protocols applied:</td><td>1994 Northridge earthquake at places shown in Figure 10; 1989 Loma Prieta earthquake at 4 sites between Santa Clara and San Francisco.</td></tr>
<tr><td>Method for observing demand:</td><td>The base excitations for 4 are known from CSMIP strong motion instruments in the building. Let PGA_1 denote the observed maximum-component peak ground acceleration recorded by these instruments. Olive View Medical center housed CSMIP station 24514, whose ground level parking lot components 360 and 90 recorded PGAs of 826.80 and 592.6 cm/sec2, respectively. Los Angeles County/USC Medical Center housed CSMIP station 24605 whose freefield components 95 and 5 recorded PGAs of 209.7 and 483.3 cm/sec^2, respectively. UCSF and Agnews Developmental Center also had strong motion instruments at or near the building. In the hospitals that did not house a strong-motion instrument, one can estimate the PGA by spatially interpolating between the two nearest strong-motion instruments, denoted below by PGA_a and PGA_b, and illustrated in Figure 10. Let d_a denote the distance from station a to the site of interest,</td></tr>
</table>

	while d_b denotes the distance to station b. Then one can estimate PGA as: $PGA = PGA_1$ *if exists* $\approx \frac{d_b}{d_a + d_b} PGA_a + \frac{d_a}{d_a + d_b} PGA_b$ *otherwise* Other demand measures were considered; see attached MS.
Method for observing damage:	Finley et al. (1996) examined all elevators and interviewed personnel in 9 public hospitals in the San Fernando Valley and northern Los Angeles basin after the 1994 Northridge earthquake on behalf of the Office of Statewide Health Planning and Development (OSHPD). OSHPD selected the hospitals for inspection by age and location, and because they were public and therefore readily accessible, without regard to or foreknowledge of damage. (This is according to the original OSHPD request for proposals, and per personal communication with Wendt [2009], a participant in the Finley et al. study). The authors' objective was to determine the effects the earthquake had on elevator systems. Eight hospitals contained 93 traction elevators and 12 hydraulic elevators. The report contains detailed assessment of each elevator, including the availability of electric power, the performance of equipment anchorage, rope guards, rail and brackets, guide shoes, and other components. The ninth hospital had incomplete damage information and is not used here. See the list of elevator installation and performance features that Finley et al. (1996) recorded in Table 3. HKA (same firm as Finley et al.) had earlier performed a similar study for OSHPD of 5 Bay Area hospitals, 4 of which had traction elevators. They visually inspected each elevator, interviewed hospital personnel, and examined repair records of corrective action taken by the elevator contractor. Naeim visited each building interviewed building personnel, and assigned a qualitative damage descriptor judgment, from among: null, none, insignificant, moderate, or heavy. Present author translated these to quantitative failure rates as follows: "insignificant" damage = 1-10% failure fraction (larger if the building most likely had fewer than 10 elevators to fail), "moderate" = 10-30%, and "heavy" = 30-100%. This assignment is crude and somewhat arbitrary, and only represent one mapping scheme among many possible.

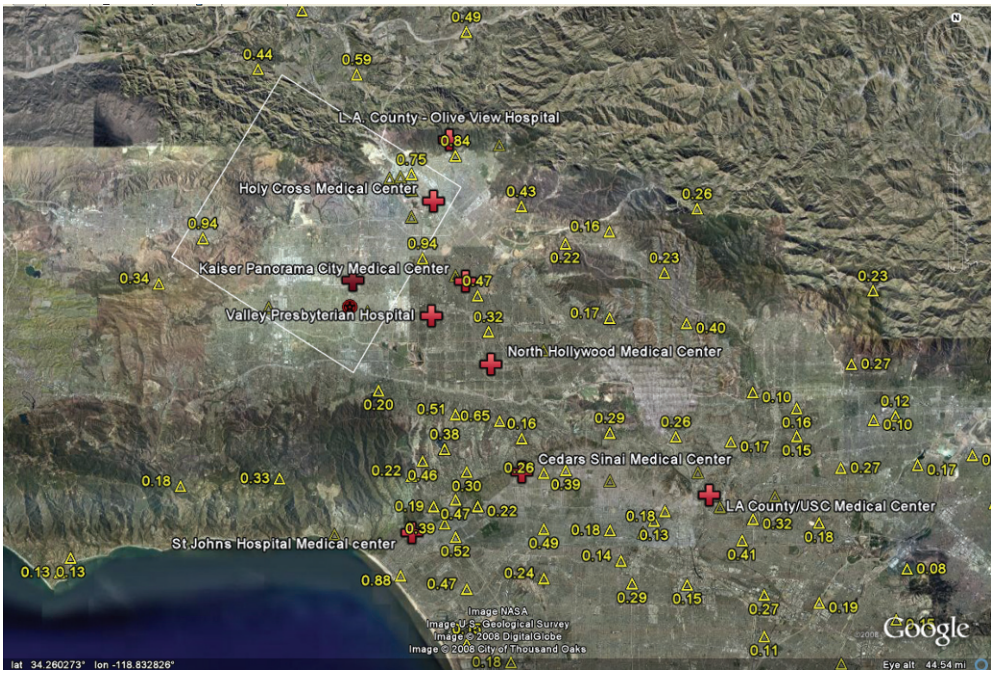


Figure 10. PGA estimated in 6 hospitals without strong-motion instruments by spatially interpolating between nearby strong-motion instruments (triangles)

Table 3. Elevator installation and performance characteristics recorded by Finley et al. (1996)

Feature	**Example**
MANUFACTURER	Dover
INSTALLATION DATE	1987
MODERNIZATION DATE	NIA
MACHINE TYPE	Geared
TOTAL CAR WEIGHT	6100
CAPACITY (Pounds)	4500
SPEED (FPM)	350
STOPS	7
CAR RAIL SIZE	15#
FISHPLATE SIZE	3/4"
BRCKT. SPACING	6'-6"
DIST. -BRKT TO FISHPLATE	2'-0"
CWT RAIL SIZE	15#
FISHPLATE SIZE	3/4"
BRCKT. SPACING	6'-6"
DIST. -BRKT TO FISHPLATE	2'-0"
CAR GUIDE SHOES	Roller
CWT GUIDE SHOES	Roller
CAR RETAINER PLATE SIZE	3/8"
CWT RETAINER PLATE SIZE	3/8"
CWT SPREADER BRKT.	None
Spacing	N/A
Thickness	N/A
SEISMIC SWITCH INSTALLED	N0
Location	N/A
Activated	N/A

Feature	Example
DERAIL. DEVICE INSTALLED	Yes
Qty/Cwt	2/Cwt
Activated	Yes
EQUIP. TIE DOWNS COMPLY	
Machine	1
Motor Gen./SCR	1
Controller	1
Rope Guards	1
BLDG CONSTRUCTION	Steel Frame
BUILDING POWER AVAIL. AFTER EARTHQUAKE	
Normal	No
Emergency	No
EQUIP. ANCHOR. FAILED	
Controller	0
Machine	0
Motor Generator	0
Governor	0
ROPE GUARD FAILURES	0
RAIL & BRACKETS	
Rail Distortion	0
Inter. Brckt Spread	N/A
Cwt Brckt Break/Bend	N/A
Car Brckt Break/Bend	0
GUIDE SHOES DAMAGED	
Car	1
Cwt	0
CWT FRAME DISTORTION	0
CAB STABILIZERS BENT	1
CAB INTERIOR DAMAGE	
Ceiling	1
Walls	0
Doors	0
HOISTWAY ENT. DAMAGED	0
HOISTWAY WALL DAMAGED	0
TAIL SHEAVE DISLODGED AND/OR TWISTED	0
SNAGGED ROPES OR TRAVELING CABLES	0
HOISTWAY SPRINKLER PIPE FAILURE	0

Table 4. Table of test results

ID	Specimen	PGA, g	Year installed	Post-1973	Equipment tie-downs comply	Failed	Controller anchorage failure	Machine anchorage failure	Motor Generator anchorage failure	Governor anchorage failure	Rope guard failures	Rail Distortion	Inter. Brckt Spread	Cwt Brckt Break/Bend	Car Brckt Break/Bend	Car guide shoes damaged	Cwt guide shoes damaged	Cwt frame distortion	Cab stabilizers bent	Cab ceiling damage	Call walls damaged	Cab doors damaged	Tail sheave dislodged and/or twisted
1	L.A. County - Olive View Hospital 1 -Service	0.84	1987	1	1	1	0	0	0	0	0	0	N/A	N/A	0	1	0	0	1	1	0	0	0
2	L.A. County - Olive View Hospital 2-Service	0.84	1987	1	1	1	0	0	0	0	0	0	N/A	N/A	0	0	0	0	1	1	0	0	0
3	L.A. County - Olive View Hospital 3-Service	0.84	1987	1	0	1	0	1	0	0	0	0	N/A	N/A	0	0	0	0	1	1	1	1	0
4	L.A. County - Olive View Hospital 4-Service	0.84	1987	1	0	1	0	1	0	1	0	0	N/A	N/A	0	0	0	1	1	1	0	0	0
5	L.A. County - Olive View Hospital 5-Passenger	0.84	1987	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0
6	L.A. County - Olive View Hospital 6-Passenger	0.84	1987	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0
7	L.A. County - Olive View Hospital 7-Passenger	0.84	1987	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
8	Holy Cross Medical Center 1	0.84	1961	0	1	1	0	0	0	0	0	1	0	1	0	0	1	1	0	1	0	1	0
9	Holy Cross Medical Center 2	0.84	1990	1	1	1	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	1	0
10	Holy Cross Medical Center 3	0.84	1961	0	1	1	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	1	0
11	Holy Cross Medical Center 4	0.84	1961	0	1	1	0	0	0	0	0	1	0	0	0	0	1	1	0	1	0	1	0
12	Holy Cross Medical Center 5	0.84	1941	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Holy Cross Medical Center 6	0.84	1946	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	Holy Cross Medical Center Kitchen service	0.84	1941	0	1	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0
15	St John Hospital - West Wing 10	0.50	1978	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16	St John Hospital - West Wing 11	0.50	1978	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
17	St John Hospital - South Wing Pass 1	0.50	1965	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	St John Hospital - South Wing Pass 2	0.50	1965	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	St John Hospital - South Wing Service 3	0.50	1965	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	St John Hospital - South Wing Service 4	0.50	1965	0	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
21	Cedars Sinai Medical Center - South Tower 1	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	Cedars Sinai Medical Center - South Tower 2	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Cedars Sinai Medical Center - South Tower 3	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Cedars Sinai Medical Center - South Tower 4	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Cedars Sinai Medical Center - South Tower 5	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Cedars Sinai Medical Center - South Tower 6	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Cedars Sinai Medical Center - South Tower 7	0.26	1975	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	Cedars Sinai Medical Center - South Tower 8	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	Cedars Sinai Medical Center - South Tower 9	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	Cedars Sinai Medical Center - South Tower 10	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	Cedars Sinai Medical Center - South Tower 11	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	Cedars Sinai Medical Center - South Tower 12	0.26	1983	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	Cedars Sinai Medical Center - North Tower 13	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	Cedars Sinai Medical Center - North Tower 14	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	Cedars Sinai Medical Center - North Tower 17	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	Cedars Sinai Medical Center - North Tower 18	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	Cedars Sinai Medical Center - North Tower 19	0.26	1983	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	Cedars Sinai Medical Center - North Tower 20	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	Cedars Sinai Medical Center - North Tower 21	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	Cedars Sinai Medical Center - North Tower 22	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	Cedars Sinai Medical Center - North Tower 23	0.26	1975	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	Cedars Sinai Medical Center - North Tower 24	0.26	1983	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	Cedars Sinai Medical Center - Brown Building 6	0.26	1954	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	Cedar-Sinai Medical Center - Thalians Building 1	0.26	1972	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
45	Cedar-Sinai Medical Center - Thalians Building 2	0.26	1972	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
46	Valley Presbyterian Hospital 1	0.38	1957	0	1	1	0	0	1	0	0	1	1	0	0	0	1	0	1	0	0	0	0
47	Valley Presbyterian Hospital 2	0.38	1957	0	1	1	0	0	1	0	0	1	1	0	0	0	1	0	1	0	0	0	0
48	Valley Presbyterian Hospital 3	0.38	1960	0	1	1	0	0	1	0	0	1	1	0	0	0	1	1	1	0	0	0	0
49	Valley Presbyterian Hospital 4	0.38	1960	0	1	1	0	0	1	0	0	1	1	0	0	0	1	0	1	0	0	0	0
50	Valley Presbyterian Hospital 5	0.38	1969	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Table 6. Table of test results (cont.)

ID	Specimen	PGA, g	Year installed	Post-1973	Equipment tie-downs comply	Failed	Controller anchorage failure	Machine anchorage failure	Motor Generator anchorage failure	Governor anchorage failure	Rope guard failures	Rail Distortion	Inter. Brckt Spread	Cwt Brckt Break/Bend	Car Brckt Break/Bend	Car guide shoes damaged	Cwt guide shoes damaged	Cwt frame distortion	Cab stabilizers bent	Cab ceiling damage	Call walls damaged	Cab doors damaged	Tail sheave dislodged and/or twisted
51	Valley Presbyterian Hospital 6	0.38	1969	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
52	Kaiser Panorama City Medical Center H1	0.33	1987	1	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
53	Kaiser Panorama City Medical Center H2	0.33	1987	1	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
54	Kaiser Panorama City Medical Center H3	0.33	1987	1	1	1	0	0	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0
55	Kaiser Panorama City Medical Center H4	0.33	1987	1	1	1	0	0	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0
56	Kaiser Panorama Hospital Stair Tower 1	0.33	1989	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	Kaiser Panorama Hospital Stair Tower 2	0.33	1989	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	Kaiser Panorama Hospital Stair Tower 3	0.33	1989	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	Northridge Hospital Medical Center 1990 Otis elevator 1	0.45	1990	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
60	Northridge Hospital Medical Center 1990 Otis elevators 2	0.45	1990	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
61	Northridge Hospital Medical Center 1990 Otis elevators 3	0.45	1990	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
62	Northridge Hospital Medical Center 1990 Otis elevators 4	0.45	1990	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
63	Northridge Medical Center 1967 Westinghouse Elevator 1	0.45	1967	0	1	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0
64	Northridge Medical Center 1967 Westinghouse Elevator 2	0.45	1967	0	1	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0
65	Northridge Medical Center 1967 Westinghouse Elevator 3	0.45	1967	0	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0
66	Northridge Medical Center 1967 Westinghouse Elevator 4	0.45	1967	0	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0
67	LA County/USC Medical Center 1	0.49	1971	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	LA County/USC Medical Center 2	0.49	1971	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	LA County/USC Medical Center 3	0.49	1971	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	LA County/USC Medical Center 4	0.49	1971	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
71	LA County/USC Medical Center 5	0.49	1971	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
72	LA County/USC Medical Center 6	0.49	1971	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
73	LA County/USC Medical Center 001	0.49	1970	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	LA County/USC Medical Center 357	0.49	1970	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	LA County/USC Medical Center 467	0.49	1971	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	LA County/USC Medical Center 667	0.49	1969	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	LA County/USC Medical Center 300A	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	LA County/USC Medical Center 300B	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79	LA County/USC Medical Center 700A	0.49	1972	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
80	LA County/USC Medical Center 700B	0.49	1972	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
81	LA County/USC Medical Center 227	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	LA County/USC Medical Center 327	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	LA County/USC Medical Center 727	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	LA County/USC Medical Center 827	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	LA County/USC Medical Center 027	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	LA County/USC Medical Center 127	0.49	1972	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	LA County/USC Medical Center Pediatrics & Womens 1	0.49	1958	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0
88	LA County/USC Medical Center Pediatrics & Womens 2	0.49	1958	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0
89	LA County/USC Medical Center Pediatrics & Womens 3	0.49	1958	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0
90	LA County/USC Medical Center Pediatrics & Womens 4	0.49	1958	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0
91	LA County/USC Medical Center Pediatrics & Womens 5	0.49	1958	0	1	1	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0	0	0
92	LA County/USC Medical Center Pediatrics & Womens 6	0.49	1958	0	1	1	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0	0	0
93	LA County/USC Medical Center Pediatrics & Womens 7	0.49	1958	0	1	1	0	0	0	0	0	1	0	0	0	1	1	0	1	0	0	0	0

Table 5. Summary of observations by failure mode and era of installation from Finley et al. (1996) data

Failure mode	*All*			*Pre-1973*		*Post-1973*	
	n	***f***	***f****	***n***	***f***	***n***	***f***
1. Controller anchorage failed	0	0.00	0.00	0	0.00	0	0
2. Machine anchorage failed	3	0.03	0.06	1	0.02	2	0.05
3. Motor generator anchorage failed	8	0.09	0.17	8	0.16	0	0
4. Governor anchorage failed	1	0.01	0.02	0	0.00	1	0.02
5. Rope guard failures	2	0.02	0.04	0	0.00	2	0.05
6. Rail distortion	27	0.29	0.57	22	0.44	5	0.12
7. Intermediate tie bracket damage	12	0.13	0.26	8	0.16	4	0.09
8. Counterweight bracket break or bend	6	0.06	0.13	6	0.12	0	0.00
9. Car bracket break or bend	4	0.04	0.09	4	0.08	0	0.00
10. Car guide shoes damaged	15	0.16	0.32	12	0.24	3	0.07
11. Counterweight guide shoes damaged	16	0.17	0.34	15	0.30	1	0.02
12. Counterweight frame distortion	12	0.13	0.26	7	0.14	5	0.12
13. Cab stabilizers bent	28	0.30	0.60	13	0.26	15	0.35
14. Cab ceiling damaged	8	0.09	0.17	3	0.06	5	0.12
15. Cab walls damaged	1	0.01	0.02	0	0.00	1	0.02
16. Cab doors damaged	5	0.05	0.11	3	0.06	2	0.05
17. Tail sheave dislodged and/or twisted	0	0.00	0.00	0	0.00	0	0.00
18. Snagged ropes or traveling cables[(a)]	26	0.28	0.55	3	0.06	23	0.53

n = number of specimens with this failure mode

f = fraction of all specimens (damaged or undamaged) with this failure mode

*f** = fraction of all damaged specimens with this failure mode

(a) Reported repairs sometimes disagree with elevator damage records; failure mode ignored

Table 6. Summary of observations by facility and era of installation

ID	Hospital	Lat	Lon	All			Pre-1973			Post-1973		
				n	N	f	n	N	f	n	N	f
1	Los Angeles County Olive View	34.3258	118.4457	7	7	1.00	0	0		7	7	1.00
2	Holy Cross Medical Center	34.2800	118.4600	5	7	0.71	4	6	0.67	1	1	1.00
3	St. John's Hosp. Medical Center	34.0313	118.4797	3	6	0.50	1	4	0.25	2	2	1.00
4	Cedars Sinai Medical Center	34.0751	118.3802	2	25	0.08	2	3	0.67	0	22	0.00
5	Valley Presbyterian Hospital	34.1939	118.4620	6	6	1.00	6	6	0.50	0	0	
6	Kaiser Panorama City Medical Center	34.2198	118.4305	4	7	0.57	0	0		4	7	0.57
7	Northridge Hospital Medical Center	34.2208	118.5334	8	8	1.00	4	4	1.00	4	4	1.00
8	L.A. County/U.S.C. Medical Center	34.0591	118.2099	12	27	0.44	12	27	0.44	0	0	
9	UC San Francisco	37.7637	122.4587	7	12	0.58	6	6	1.00	1	6	0.17
10	Agnews Developmental Ctr, Sta Clara	37.4075	121.9326	0	2	0.00	0	2	0.00			
11	El Camino Hospital, Mountain View	37.3683	122.0798	1	5	0.20	1	5	0.20			
12	Oak Knoll Naval Hospital	37.7689	122.1459	0	3	0.00	0	3	0.00			
	Total			55	115		36	66		19	49	

"n" indicates the number of failed specimens

"N" indicates the total number of specimens

"f" indicates failure rate, n/N

Table 7. Correlation among era installed and failure modes. Dark highlighted cells indicate correlation coefficient $|\rho| \geq 0.5$. Light highlights indicate $0.25 \leq |\rho| < 0.5$. Note post-1973 installation tends to increase the chance of cab stabilizer failure, and decrease the chance of damaged counterweight brackets, but the correlation is not strong.

Failure mode	Post-1973	Controller anchorage failure	Machine anchorage failure	Motor Generator anchorage failure	Governor anchorage failure	Rope guard failures	Rail Distortion	Inter. Brckt Spread	Cwt Brckt Break/Bend	Car Brckt Break/Bend	Car guide shoes damaged	Cwt guide shoes damaged	Cwt frame distortion	Cab stabilizers bent	Cab ceiling damage	Cab walls damaged	Cab doors damaged	Tail sheave dislodged and/or twisted
Post-1973	1.00	0.00	0.05	-0.18	0.10	0.14	-0.12	-0.14	-0.28	-0.23	0.11	-0.03	-0.09	0.33	0.05	0.10	-0.07	0.00
Controller anchorage failure		1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Machine anchorage failure			1.00	0.16	0.57	-0.03	-0.12	-0.04	-0.03	-0.04	-0.08	-0.08	0.11	0.28	0.38	0.57	0.23	0.00
Motor Generator anchorage failure				1.00	-0.03	-0.05	0.31	0.34	-0.08	-0.07	0.07	0.47	0.00	0.47	-0.09	-0.03	-0.07	0.00
Governor anchorage failure					1.00	-0.02	-0.07	0.00	0.00	-0.02	-0.05	-0.05	0.27	0.16	0.34	-0.01	-0.02	0.00
Rope guard failures						1.00	-0.09	-0.06	-0.04	-0.03	-0.07	-0.07	0.39	0.23	-0.05	-0.02	-0.04	0.00
Rail Distortion							1.00	0.60	0.41	0.33	0.43	0.71	0.18	0.25	0.14	-0.07	0.27	0.00
Inter. Brckt Spread								1.00	0.42	0.55	0.19	0.16	-0.05	0.20	-0.09	0.00	-0.09	0.00
Cwt Brckt Break/Bend									1.00	0.81	0.13	-0.01	0.17	-0.16	0.16	0.00	0.16	0.00
Car Brckt Break/Bend										1.00	0.20	-0.10	-0.08	-0.14	-0.07	-0.02	-0.05	0.00
Car guide shoes damaged											1.00	0.34	-0.17	0.35	-0.03	-0.05	-0.10	0.00
Cwt guide shoes damaged												1.00	0.25	0.38	0.27	-0.05	0.40	0.00
Cwt frame distortion													1.00	0.10	0.45	-0.04	0.48	0.00
Cab stabilizers bent														1.00	0.13	0.16	-0.05	0.00
Cab ceiling damage															1.00	0.34	0.78	0.00
Cab walls damaged																1.00	0.44	0.00
Cab doors damaged																	1.00	0.00
Tail sheave dislodged and/or twisted																		1.00

Table 8. Quality tests

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	NA		
Are θ and β within 20% of past results? If not discuss.	Y		
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y		
Do you believe the demand with 10% failure probability?	Y		
Discussion. Re past results, Eidinger & Goettel (1998) offer a fragility function for moderate damage to rails in traction elevators that comply with UBC 1994 with $\theta = 0.35g$ and $\beta = 0.5$, both within 20% of these results. Re do you believe, Naiem and HKA data generally support.			

Table 9. Extrapolation to other detailed conditions and to average conditions

Condition (describe)	From tests?	DS1		DS2		DS3	
		θ	β	θ	β	θ	β
Best: post-1973	Y	0.39	0.40				
Moderate							
Worst: pre-1973 installation	Y	0.32	0.60				
Average or unknown	Y	0.35	0.40				
Basis for extrapolation: data. What factors affect θ and β? The principal failure modes are cab stabilizers bent or rail distortion. Examination of Table 7 shows that post-1973 construction tends to correlate with bent cab stabilizers. Pre-1973 tends to correlate with counterweight bracket damage, but neither correlation is strong.							

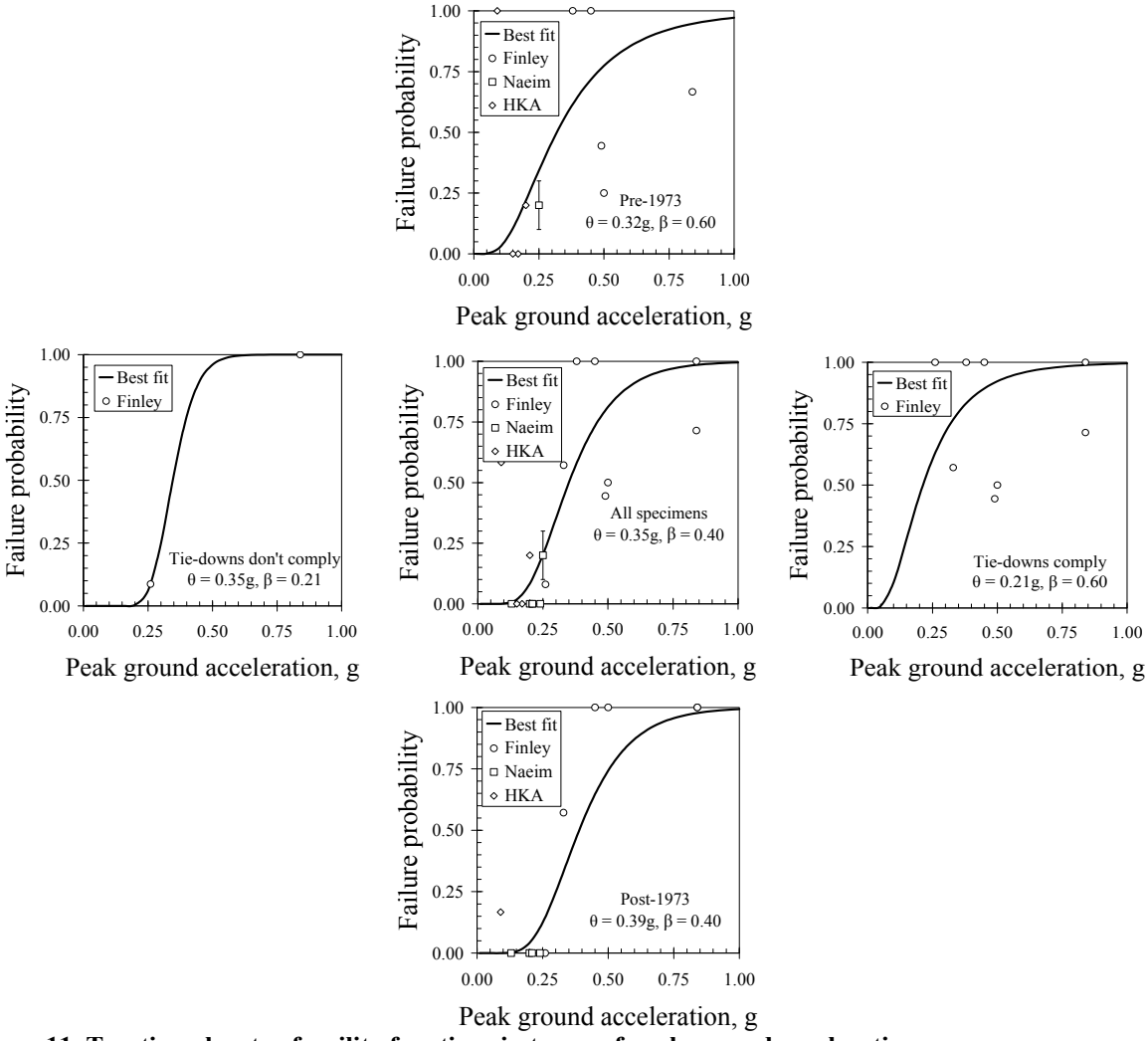


Figure 11. Traction-elevator fragility functions in terms of peak ground acceleration

REFERENCES CITED

Ayres, J.M. and T.Y. Sun, 1973. Nonstructural damage. *The San Fernando, California, Earthquake of February 9, 1971*. U.S. Department of Commerce, National Ocean and Atmospheric Administration, 1 (B), 736-742.

Ayres, J.M., T.Y. Sun, and F.R. Brown, 1973. Nonstructural damage to buildings. *The Great Alaska Earthquake of 1964: Engineering*, Division of Earth Sciences, National Research Council, National Academy of Sciences, Washington, DC, 346-456.

Eidinger, J. and K. Goettel, 1998. Benefits and costs of seismic retrofits of non structural components of hospitals, essential facilities, and schools. *Proc., Seminar on Seismic Design Retrofit and Performance of Nonstructural Components, ATC 29-1*, Applied Technology Council, Redwood City, CA, 491-504

Finley, J., D. Anderson, and L. Kwon, 1996. *Report on the Northridge Earthquake Impacts to Hospital Elevators*. Contract No. 94-5122. California Office of Statewide Health Planning and Development (OSHPD), Sacramento, CA

Gates, W.E. and G. McGavin, 1998. Lessons learned from the 1994 Northridge earthquake on the vulnerability of nonstructural systems. *Proceedings of the Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components, ATC 29-1*. Applied Technology Council, 93-106.

(HKA) Hesselberg, Keesee, and Associates, Inc. 1992. *Report on the Loma Prieta Earthquake Impacts to Hospital Elevators*. Prepared for Office of Statewide Health Planning and Development, Sacramento CA.

Naeim, F., 1997. *Response of Instrumented Buildings to 1994 Northridge Earthquake, an Interactive Information System*. John A Martin and Associates, Inc., Los Angeles. CD-ROM.

Wendt, T. 2009. Personal communication.

Revision history

1.0	01 Nov 2008	Initial release w Frag Spec 1.5
2.0	02 Dec 2008	Change PGAs to be based on 2 nearest stations, not Somerville map
3.0	13 Apr 2009	Reconcile PGA with hydraulic elevators. Add Naiem data. Check Naiem CSMIP software. Correct age of Cedars Sinai elevators. Eliminate snagged ropes and traveling cables as failure mode.
4.0	15 July 2009	Add HKA Loma Prieta data. Doesn't change fragility functions much.