Preferred Direction of Damage to Concrete Block Fences in the M6.7 Northridge Earthquake of 17 January 1994

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The Northridge earthquake toppled three times more concrete block fences that were oriented east-west than those oriented north-south. Toppled fences were twice as likely to fall to the north as to the south. This was discovered during damage causation studies for insurance companies in our survey of more than 200 single-family residences within 29 km of the epicenter. Two hundred nineteen fences were built within 11 degrees of either north (55%) or east (45%), providing an opportunity to study the effect of orientation. Of those fences that were completely toppled, 19 were oriented east-west, while only 7 were oriented north-south. This preferred direction of damage for toppled fences was observed in all four quadrants about the epicenter and at distances of up to 17 km. In the NW quadrant, immediately above the aftershock zone, all toppled fences were oriented E-W, none were oriented N-S. The 58 fences oriented within 11 degrees of either NE or SE had no preferred direction of damage. In general, the failure rate for all 297 fences correlated with Modified Mercalli Intensity, location on alluvium as opposed to bedrock, and lack of structural reinforcement.
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INTRODUCTION

We performed over 200 damage causation studies for insurance carriers in the Los Angeles basin soon after the Northridge earthquake on 17 January 1994 (Figure 1). Damages to structures, primarily single-family homes, were observed, photographed, sketched, and documented in detail (Snyder and Borchardt 1998).[1] During the course of our investigations, the engineers and geologists who performed the documentation conjectured that there was an observable pattern to the damage in the epicentral region. It appeared that the most extensively damaged concrete block or masonry fences were oriented in an east-west direction (Figure 2). The initial damaging seismic motion was roughly parallel the direction of thrust fault motion: from south to north. This work was a test of that association.

Although damage to concrete block fences was mentioned in earthquake reconnaissance reports (Hall 1995), no other detailed surveys have been performed even though

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[1]The complete data set for all 297 concrete block fences is at www.soiltectonics.com in the Data Archive.

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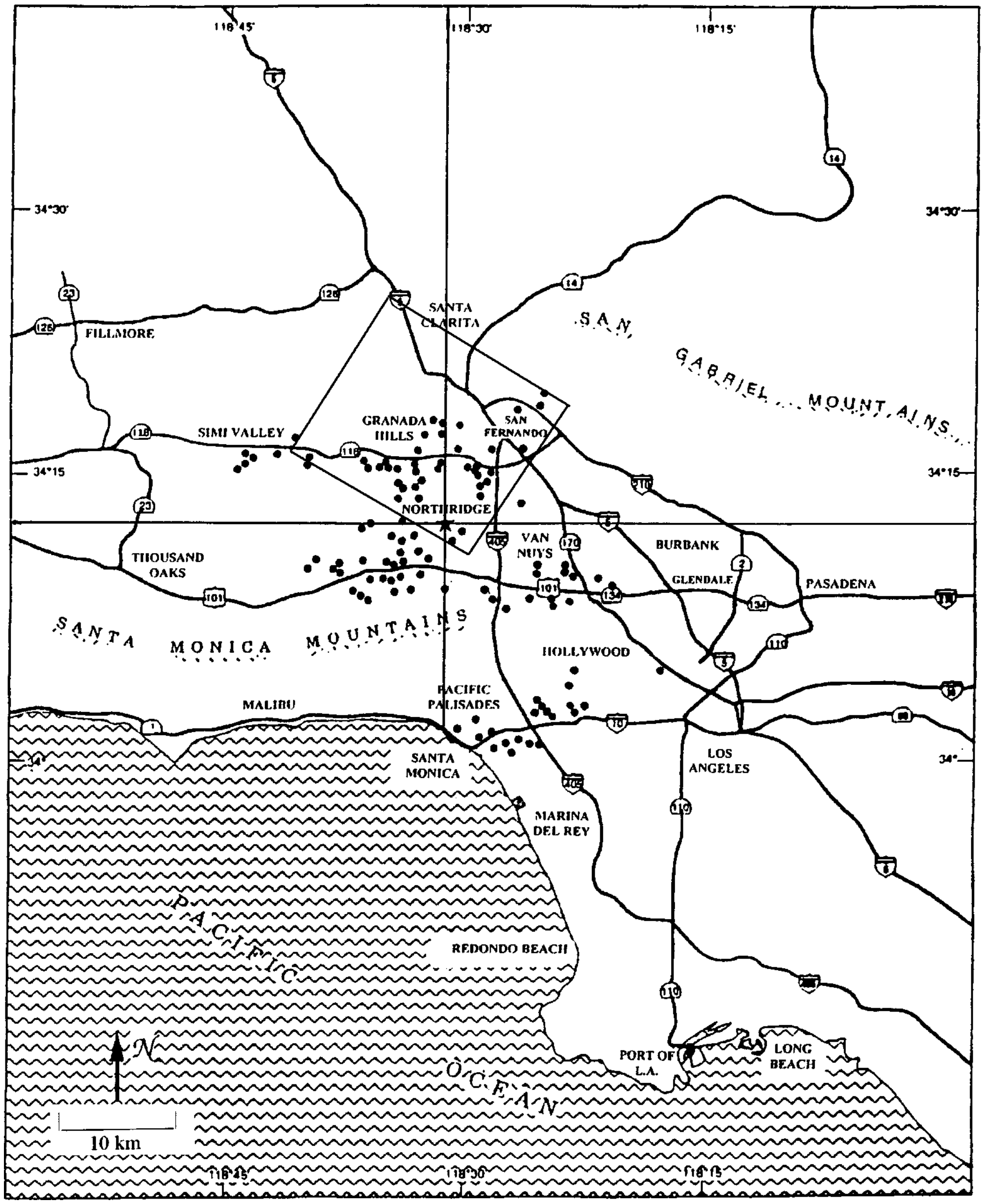

Figure 1. Location of study sites. Projected fault rupture plane from Wald and Heaton (1994).

their generally uniform construction makes the fences nearly ideal for the study of the effects of orientation. Orientation studies following earthquakes have been made since the beginning of seismology. Anecdotal accounts after the M6.8 1868 Hayward earthquake, for instance, mentioned the tendency of chimneys and houses to fall either north or south, but not east or west in that event (Lawson 1908). Unfortunately, investigators

Figure 2. Typical concrete block fences used to demarcate property lines in the San Fernando Valley. An E-W oriented fence is in the foreground and a N-S oriented fence is in the background.

only rarely record compass or view directions along with data or photos of earthquake damage (e.g., Borchardt 1991). Our own recognition of the importance of direction was somewhat dependent on the fortuitous correspondence of the orientation of the street grid with the approximate rupture direction in this quake.

Concrete block fences are common to nearly all of the properties that we evaluated and are of remarkably consistent construction. They are usually unreinforced, unrestrained, without significant foundations, and laid out along property lines, which in the San Fernando Valley, generally are oriented E-W and N-S. We had photographs, scale drawings, written measurements, and other documentation for all of the fences encountered at the residential structures we evaluated.

Concrete block fences are nearly ideal for studying certain aspects of orientation. No matter what the degree of reinforcement, each fence clearly has a seismically strong direction and a seismically weak direction. E-W oriented fences are more likely to be toppled by motion directed from the north or south than by motion directed from the east or west; N-S oriented fences are more likely to be toppled by motion from the east or west than by motion from the north or south.

METHODS

All insurance reports we prepared during 1994 for the Northridge earthquake were reviewed for documentation concerning concrete block fences. We believe that these reports are fairly representative of the geographic distribution of damage to single-family residences during the main shock. Aftershocks apparently were not responsible for any of the damage, as we were not recalled to properties that were assessed first. The reports were compiled for several large insurance companies with area-wide jurisdiction and with no previously declared restrictions on the purchase of insurance. There probably were some sociological and geographical biases in the purchase of insurance and the tendency to file a claim, but we are unaware of any that were significant enough to affect our study. Of course, by its nature this type of study cannot be representative of the degree of damage experienced by the community as a whole. We made no effort to evaluate properties for which no insurance claims were made. Nevertheless, the data set appears highly representative for comparisons involving fence orientation.

The 297 fence descriptions were categorized as follows: no damage, cracked but stable, cracked and wobbly, cracked and leaning, toppled in places, and completely toppled.[1] The first two categories were considered "unfailed fences," that is, they either had no damage or were structurally stable despite new, essentially cosmetic cracks. The last four categories were considered "failed fences," which we recommended for removal and replacement.

In addition to damage descriptions, other information also was gathered from the reports. Based on the geological section in each report, a site was classified as being built upon either alluvium or bedrock. A local Modified Mercalli Index (MMI) value was also entered in the database for each site, based on the site observations of the reporting engineer or geologist and published isoseismal maps. Fence reinforcement, or its lack thereof, was determined either from text or from photos. In some cases, this could not be confidently determined, and thus the classification was listed as unknown. Last, fence dimensions such as length, height, and orientation were recorded. The sites were located on 1:24,000 scale topographic maps and the distance and azimuth for each site was noted with respect to the epicenter.

We tested two oriented grids by using data from the 297 fully documented fences. The N-oriented grid used only those fences oriented within 11 degrees of N or E. We considered 11 degrees to be within construction and measurement tolerances. This reduced the data set to 219 fences, with 186 having failed. The NE-oriented grid used only those fences oriented within 11 degrees of NE or SE. This reduced the data set to 51 fences, with 28 having failed.

Table 1. Failure of concrete block fences as a function of distance from the epicenter

Distance km	Unfailed	Failed	Total	% Failures	Cumulative Failures, %	Failure Rate, %
0 to 5	16	49	65	25	25	75
5 to 10	11	73	84	38	63	87
10 to 15	22	28	50	15	78	56
15 to 20	16	21	37	11	89	57
20 to 25	26	21	47	11	99	45
25 to 30	13	1	14	1	100	7
Total	104	193	297			65

RESULTS AND DISCUSSION

ANALYSIS OF FAILED FENCES

As mentioned, the fully documented data set included 297 fences, 193 of which were "failed fences" that we recommended for replacement. We examined the data for failed fences to study the effects of distance and direction from the epicenter.

Damages vs. Distance

Within the data set, over sixty percent of the failed fences were within 10 km of the epicenter and nearly all of the fences were within 25 km of the epicenter (Table 1). The failure rate at these sites was over 75% within 10 km of the epicenter. The failure rate decreased to 45% at 20 km, abruptly falling to 7% at 25 km. A comprehensive survey of *all* fences in the Northridge area undoubtedly would yield much lower failure rates, but the effect of distance probably would be similar.

Damage vs. Distance and Direction

For this analysis we divided the data set into quadrants centered on the epicenter (Figure 1). Again, the sites within 10 km generally had the most failed fences. The group of failures at 20–25 km in the SE quadrant reflects the localized damage that occurred in Santa Monica presumably due to basin edge seismological effects (Graves et al. 1998).

Earthquakes normally have the most intense shaking in the direction of fault rupture, a process called "forward rupture directivity" and documented with strong motion records for Northridge by Somerville and Smith (1996) and Somerville et al. (1996). At first glance, Figure 3 would appear to be evidence for this: 62% of the failed fences in our data set were north of the latitude of the epicenter, in the direction of rupture. However, the low density development and the dominantly bedrock sites in the Santa Monica Mountains also could be responsible for the lesser number of failed fences south of the epicenter. There were only a few failed fences over 10 km north of the epicenter, although the developed area in the San Fernando Valley extended to stiff soil and bedrock sites over 15 km to the north.

Fences built on alluvium had a greater tendency to fail than those built on bedrock (Figure 4). Although 14% of the fences were on bedrock, only 9% of the failed fences and only 3% of the toppled fences were on bedrock. (The one toppled fence on bedrock

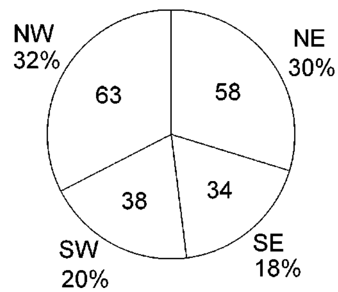

Figure 3. Numbers of failed fences by quadrant.

actually was founded on 5 m of fill; a parallel fence built entirely on bedrock did not fail.) Most fences lacked adequate foundations, so foundation type could not have been a significant factor in preventing damage on bedrock as opposed to alluvium.

At least a few fences in each damage category were found in all MMI zones assigned by the site evaluators (VI to IX), so fence failure was not the sole criteria for the MMI designation. Nevertheless, the tendency to fail was directly related to the assigned MMI (Figure 5). Fence reinforcement dropped the failure rate from 79% to 27%. Only one reinforced fence toppled completely.

ANALYSIS OF FENCE ORIENTATION VS. DAMAGE

N-Oriented Grid

In collecting the data, we were careful to determine the compass orientation of every fence for each damage category. Data were normalized to account for differences in the numbers of fences exposed to the earthquake. There were 115 fences oriented N-S and only 104 fences oriented E-W (Table 2).[1] To make the data for both orientations comparable, the number of E-W fences in each category was multiplied by the factor, 1.11 (i.e., 115/104). Thus, the 19 E-W oriented fences that toppled would represent 21 fences in comparison to the 7 N-S oriented fences that actually toppled (Table 2). Overall, the preferred direction of damage favoring the toppling of E-W fences therefore was 75%. In other words, the E-W fences were three times as likely to topple as N-S fences.

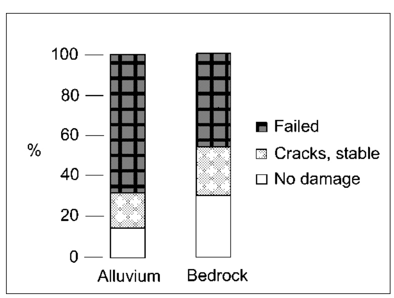

Figure 4. Fences on alluvium had a greater tendency to fail than those on bedrock.

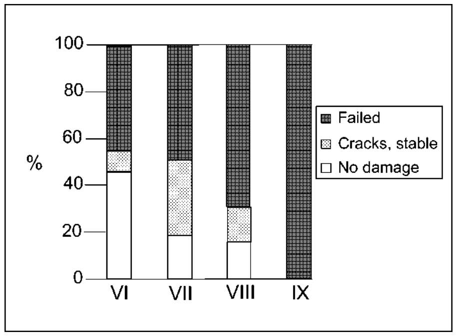

Figure 5. Fence damage in relation to Modified Mercalli Intensity.

The scaling factor used above assumes that the failure rate would have remained the same regardless of the number of fences observed. Support for this assumption comes from the fact that, overall, there were about as many N-S fences (115) in the data set as E-W fences (104) (Table 2). If fence toppling had been the only motivation for the insurance claims, we probably would have observed more E-W fences than N-S fences.

Each damage category included measurements for between 13 and 63 fences (Table 2). The preferred direction of damage (preference for damage to E-W fences) ranged from 39% for stable fences that were merely cracked to 75% for fences that were completely toppled. The categories "cracks, wobbles," "cracks, leaning," and "toppled in places" had preferences ranging from 46% to 49%—close to the random value of 50%. This damage, therefore, does not appear to involve directed motion.

It is possible that a fence may have been cracked and unstable before the earthquake due to settlement or previous earthquakes. A completely toppled fence, however, could confidently be attributed to the earthquake because it clearly was not down before 17 January 1994. A completely toppled fence thus serves as a good measure of strong ground motion, whereas an unstable fence requires subjective interpretation.

Table 2. Analysis of preferred direction of damage on the north-oriented grid

	N-S	E-W	Sum	F(N/E)	E-W©	Sum©	% E-W
No Damage	17	16	33	1.11	17.7	34.7	51
Cracks, Stable	21	12	33	1.11	13.3	34.3	39
Cracks, Wobbles	29	22	51	1.11	24.3	53.3	46
Cracks, Leaning	7	6	13	1.11	6.6	13.6	49
Toppled in Places	34	29	63	1.11	32.1	66.1	49
Completely Toppled	7	19	26	1.11	21.0	28.0	75
Total	115	104	219	1.11	115.0	230.0	50

N-S=Number of damaged N-S oriented fences; E-W=Number of damaged E-W oriented fences; F(N/E) =Normalization factor [Total number of N-S fences/Total number of E-W fences]; E-W©=F(N/E) X number of E-W fences; Sum©=N-S+E-W©; % E-W=Preferred direction of damage [Percentage of fences that were oriented E-W as opposed to N-S]

Table 3. Preferred direction of damage for toppled fences at various distances from epicenter

Distance, km	All Fences Surveyed				Toppled Fences				
	N-S	E-W	Sum	F(N/E)	N-S	E-W	E-W©	Sum©	% E-W
0 to 5	30	30	60	1.00	2	9	9.0	11.0	82
5 to 10	38	37	75	1.03	4	5	5.1	9.1	56
10 to 15	19	20	39	0.95	1	3	2.9	3.9	74
15 to 20	12	8	20	1.50	0	2	3.0	3.0	100
20 to 25	9	6	15	1.50	0	0	0.0	0.0	0
25 to 30	7	3	10	2.33	0	0	0.0	0.0	0
Sum	115	104	219	1.11	7	19	21.0	28.0	75
% of Total					6	18			

N-S=N-S oriented fences; E-W=E-W oriented fences; F(N/E)=Normalization factor [Number of E-W fences/Number of N-S fences]; E-W©=F(N/E) X Toppled E-W fences; Sum©=N-S+E-W©; % E-W=Preferred direction of damage [Percentage of fences that were oriented E-W as opposed to N-S]

Many fences toppled in places because they were not reinforced in their upper courses. Of the 63 fences that were toppled in places, about half were oriented E-W and half N-S (Table 2). Unfortunately, the direction of block fall was seldom discernible by the time we did the site visits. Residents quickly picked up any blocks that had fallen onto adjacent properties, but we were able to document the direction of fall for some of them. Cement blocks that fell from the partially toppled E-W oriented fences tended to fall to the north (15) more often than toward the south (9), while those from the N-S oriented fences tended to fall toward the west (7) more often than toward the east (4). Leaning fences displayed a similar pattern (6 vs. 4 and 7 vs. 5). It could be argued that a leaning fence supported by wood shims would be a toppled fence in the absence of those shims. However, leaning fences clearly survived both the initial pulse and the cyclic shaking that occurred throughout the earthquake.

The 75% preferred direction of damage for the 26 completely toppled fences was studied in more detail by evaluating the data for each quadrant.[1] Although this reduced each data set to only 4 to 9 fences, the general tendency for E-W fences to topple was replicated for all four quadrants. The data for the NW quadrant, immediately above the aftershock zone and up-dip from the hypocenter (Figure 1), were particularly striking. Seven E-W fences toppled, while no N-S fences toppled. The N-S fences in this quadrant tended to be cracked and wobbly even though they did not fall down. As shown by Paret et al. (1998), tall structures damaged in the Northridge event were displaced north regardless of the orientation of their seismically strong directions. Similarly, the toppled fences in this study tended to fall to the north (65%) rather than to the south (35%).

All toppled fences on the N-oriented grid were within 17 kilometers of the epicenter, with the preferred direction of damage persisting within each of the 5-km distance categories (Table 3). Overall, 18% of the E-W oriented fences in the study were completely toppled by the earthquake, compared to only 6% of the N-S oriented fences.

Aside from the category of "complete toppling," E-W and N-S oriented fences experienced about the same relative amounts of damage during the Northridge earthquake. The production of cracks and the toppling of individual blocks apparently occurred throughout the duration of the earthquake and showed little preferred direction of damage. Complete toppling, on the other hand, appears to have occurred as a result of a different kind of motion.

With these concrete block fences, complete toppling results from total failure or overturning at the foundation level. Complete toppling only occurs with movement of the fence as a solitary unit. The toppled fences seldom showed any evidence that they had experienced more than a quarter-cycle of motion (Figure 2). Thus we suspect, in the light of Paret and Borchardt (1995) and Paret et al. (1998), that many of these fences toppled in response to motion that was parallel to the direction of rupture propagation. The effect was particularly dramatic in the NW quadrant, immediately above the aftershock zone. Here, only fences oriented E-W were toppled; none were oriented N-S. It appears that fences that escaped the initial motion without toppling were then subjected to cyclic motion that produced numerous shear cracks and other types of damage apparently unrelated to direction.

NE-Oriented Grid

As mentioned, 51 of the fences were oriented within 11 degrees of NE or SE, with 28 of these being failed fences. Eighteen of the failed fences were oriented NE-SW, while 10 were oriented NW-SE. The complete NE-oriented data set, however, had 33 fences that were oriented NE-SW and only 18 that were oriented NW-SE, a normalization factor of 1.8. This yields a normalized value of 18 (i.e., 10×1.8) failed fences for the NW-SE orientation. Thus the number of failed fences for both orientations is equivalent and the NE-oriented grid shows no evidence for preferred damage in either the NE or the NW directions. The preferred direction observed on the N-oriented grid would have toppled NE- and SE-oriented fences in equal numbers and would not have been detected on the NE-oriented grid.

CONCLUSIONS

1. The Northridge earthquake toppled about three times more concrete block fences that were oriented E-W than those oriented N-S.

2. The production of cracks and the toppling of individual blocks apparently occurred throughout the duration of the earthquake and showed little preferred direction of damage.

3. Complete toppling, on the other hand, appears to have occurred as a result of overturning at the foundation level, with fences moving as a solitary unit and showing no evidence that they had experienced more than a quarter-cycle of motion parallel to the direction of rupture propagation.

4. The effect was particularly dramatic in the NW quadrant, immediately above the aftershock zone where only fences that were oriented E-W were toppled.

5. Completely toppled fences were almost twice as likely to fall to the north as to the south.

6. All types of fence damage diminished with distance, except for fences in the Santa Monica area.

7. Fence failure was related to Modified Mercalli Intensity, with half of the investigated fences failing at VI and all fences failing at IX.

8. Fences on alluvium were twice as likely to fail as those on bedrock.

9. Except for one instance, steel-reinforced fences did not fail.

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