Performance-Based Damage Assessment and Design Verification of U.S. Housing in Extreme Earthquake and Hurricane Events

by

Jay H. Crandell[1] and William Freeborne[2]

ABSTRACT

This paper presents an evaluation of U.S. residential construction with respect to the actual performance of single-family detached dwellings subjected to extreme earthquakes and hurricanes. Design and construction implications are also addressed in a scientifically rigorous approach based on statistical sampling of the affected housing populations, engineering analysis, and fragility modeling. Such an approach is believed to be an effective means to identify performance issues, evaluate the strength of cause-and-effect relationships, and properly focus attention on cost-effective solutions to performance problems that will improve future design methods and construction practices.

KEYWORDS: Houses; hurricanes; earthquake; performance; design; assessment; damage; statistics; fragility.

1.0 INTRODUCTION

In this study, the "experience" of conventional residential construction (light-frame wood) is evaluated with respect to single-family detached (SFD) housing performance in the Northridge Earthquake and Hurricane Andrew using a scientifically sound experimental approach. Major seismic events cause damage to lateral resisting wall systems in conventional wood-frame construction and major wind events often cause damage to roof systems. Since these systems tend to predominate the structural risk to homes in earthquakes and hurricanes, understanding their actual performance is essential to understanding the overall performance of residential construction.

The objective of this paper is to evaluate the actual performance of homes during the Northridge Earthquake and Hurricane Andrew using statistical data on key factors such as construction characteristics, damage frequency, ground motions, wind speed, and system strength estimation. The current approaches to seismic design and wind design are also evaluated by investigating the ability to predict the actual damage and explain certain fundamental cause-and-effect relationships.

2.0 EVENT CHARACTERIZATIONS

2.1 Northridge Earthquake

The Northridge Earthquake occurred at 4:30 a.m. on January 17, 1994. Its epicenter was located in a densely populated area of Los Angeles County near the community of Northridge. Over 30 deaths were reported as a direct result of the tremor, and a total death toll of 58 was attributed to both direct and indirect causes [1]. Fortunately, relatively few deaths were associated with single family dwelling construction even though most people were in their homes at the time of the tremor. Overall property loss estimates range from $20 to $30 billion. While this earthquake was the most costly natural disaster experienced in the United States, its magnitude (Richter Scale M_L = 6.4, Surface Wave Magnitude M_S = 6.8, Moment Magnitude M_W = 6.7) was modest in terms of other more severe earthquakes. The Northridge Earthquake produced an unprecedented set of

[1]Director, Structures and Materials Division, NAHB Research Center, Inc., 400 Prince George's Blvd, Upper Marlboro, MD 20774-8731 (www.nahbrc.org)
[1]Mechanical Engineer, Office of Policy Development and Research, U.S. Department of Housing and Urban Development, 451 Seventh Street, S.W. – Room 8132, Washington, DC 20410 (www.hud.gov)

strong motion records, including more than 250 records considered representative of free field ground motion [2]. The recorded strong ground motions were characterized by a large degree of variation between sites at comparable distances from the source. Several different causes of spatial variation in ground motions have been recognized which are systematic and predictable to some extent. Strong ground motions are influenced by the characteristics of the seismic radiation from the source, by the process of wave propagation between the earthquake source and the recording site, and by local site effects [3].

2.2 Hurricane Andrew

Hurricane Andrew struck a densely populated area of southern Florida on August 24, 1992, with peak winds in excess of 78.2 m/s (175 mph) recorded at one location [4]. Using advanced hurricane modeling techniques and available wind speed data, the estimated over-land wind field of Hurricane Andrew was modeled as shown in Figure 1 [5]. The winds produced by Hurricane Andrew were estimated to have mean recurrence interval of about 300 years [6]. Because of the distance of the housing stock from the shoreline, most of the damage was related to wind, rain, and wind-borne debris — not storm surge.

3.0 DAMAGE ASSESSMENT METHODOLOGY

The objectivity of the damage assessment method hinges on the use of sampling procedures to gain a valid representation of the performance of the population of affected homes and to avoid bias toward less severe or more severe occurrences of damage. This report focuses on the study of single-family detached (SFD) housing. The sampling method and damage rating approach are briefly described below. For a more detailed treatment, the reader is referred to the original studies [7][8].

For the Northridge Earthquake, a 16.1 km (10 mi) radius around the epicenter was selected as a damage zone for study. Postal regions—as defined by five-digit zip codes that fell within the damage zone or intersected its border—were used as the basis for a random selection of homes from property tax records. There were 183,514 SFD home entries in the property tax database for the designated zip codes. Seventy-five sites were randomly selected by street address from the tax record database. The home at the selected address was surveyed along with two homes on either side—a total of five homes per site. The survey teams visited 75 sites resulting in 341 usable survey forms.

For Hurricane Andrew, over 600 randomly sampled homes experiencing the highest winds were assessed using detailed field survey forms. The randomly determined damage study locations are shown in Figure 1. The sample was drawn from a street map. In the first stage, a random sample of map grid areas was made. Within the sampled grids, a random sample of streets was drawn. All homes on the sampled streets were surveyed, with exception of those homes on a street that were not surveyed at the end of a day. A total of 466 survey forms were deemed suitable for analysis.

In each survey, all of the sample homes were visited by one of several assessment teams to document the housing characteristics and the level of performance. Survey forms were used to document about 60 construction characteristics and 30 damage characteristics for each home. Photographs were taken of each assessed property. For each category listed on the survey form, earthquake or wind damage was graded according to four levels of severity:

- NONE: no visible damage;
- LOW: components are stressed, but in functional condition (i.e., minor cracking of stucco or minor loss of roof sheathing);
- MODERATE: evidence of severe stress, permanent deflection, or near failure in any structural system (i.e., severe cracking of stucco or loss of many roof sheathing panels without collapse of the structure or roof system); and,
- HIGH: partial or complete failure (i.e., collapse) of any structural system.

Case studies of rare instances of extreme damage were also conducted for each event, but they are beyond the scope of this paper. Similarly, statistical surveys and case studies were also performed for multi-family low-rise and single-family attached forms of residential construction.

4.0 CONSTRUCTION CHARACTERISTICS AND DAMAGE STATISTICS

4.1 Northridge Earthquake Survey

The SFD housing characteristics are briefly summarized in Table 1. Using information provided by the property tax record database and inspectors with the Department of Building and Safety, it was determined that about 90 percent of the homes in the sample were built prior to the 1971 San Fernando Valley Earthquake when simple prescriptive requirements were normal to SFD home construction. About 60 percent of the surveyed homes were built during the 1950s and 1960s. House age ranged from the 1920s to the early 1990s. SFD homes were typically one-story and nearly two-thirds had an attached garage. Styles of SFD homes ranged from expensive custom homes to affordable, older homes. As expected, all homes surveyed had wood exterior wall framing and most did not use structural sheathing for wall bracing. Instead, wood let-in braces, Portland cement stucco, and interior wall finishes provided lateral resistance. Homes on crawlspace foundations outnumbered those on concrete slabs by almost two-to-one, despite a notable increase in the use of slab-on-grade foundations since the 1960s. Most of the crawlspace foundations used full-height concrete or masonry stem walls, not cripple walls.

The performance of SFD homes is shown in Table 2. The table is broken into observed damage of the homes sampled and estimates of damage for the entire population of homes within the survey area. Confidence intervals at the 95 percent level are shown for each estimate.

Damage to structural elements—foundation, wall framing, and roof framing—was limited to a small proportion of surveyed homes. In general, SFD homes suffered minimal damage to elements that are critical to the safety of occupants. Of the structural elements, damage was most common in the foundation system. The small percentage of surveyed homes that experienced moderate to high foundation damage were located in areas that endured localized ground effects or problems associated with hillside sites. The localized ground effects included fissures or ground settlement that cracked foundations. For hillside sites, partial slope failures contributed to the foundation damage.

Interior and exterior finishes suffered more widespread damage than foundation and framing, with only about half the buildings escaping unscathed. However, the great majority of damage was limited to the lowest rating categories. Stucco was observed on nearly all home exteriors. Damage to stucco usually appeared as hairline cracks radiating from the corners of openings—particularly larger openings such as garage doors—or along the top of the foundation. Interior finish damage paralleled the occurrence of exterior finish (stucco) damage. Resilient finishes—such as wood panel or lap board siding—fared well and often showed no evidence of damage even when stucco on other areas of the same building was moderately damaged.

The Chi-square test was used—at a 95 percent level of confidence—to judge statistical significance of various conditions on the outcome of a home's performance. The inferences initially designated for study by the Chi-square test included observed performance versus:

- peak ground acceleration estimates,
- age of the home,
- roof type
- number of stories, and
- foundation type.

Chi-square analyses requires a large number of observations in each category to produce valid results. Thus, the analysis was limited to the exterior damage rating as the performance indicator since it represented the greatest extent of damage. Also, the low, moderate, and high damage ratings were grouped such that a damage/no-damage test was applied. Except for foundation type, all inferences were inconclusive.

Using only data from one-story homes, comparison of crawlspace versus slab-on-grade foundation construction shows a significant difference in the level of damage to the stucco used on one-story homes. Single-story homes with slab foundations exhibited damage to exterior finishes in about 30 percent of the cases, while homes on crawlspace foundations with masonry or concrete stem walls approached a 60 percent rate of occurrence. Since the majority of crawlspace homes in the survey area were built before 1960 while nearly three-quarters of slab homes were built after 1960, stucco performance alone may not be sufficient to conclude that one foundation type is necessarily better than another. There may be factors influencing stucco performance other than merely foundation type, such as house age.

Case studies of damage were conducted on 54 SFD homes that experienced rare, severe damage. The most notable sources of structural damage to these case study homes were related to ground conditions (e.g., fissures and settlement) and hillside construction conditions (e.g., weak foundation connections or partial slope failures). Damage to wall finishes, contents, mechanical equipment, masonry chimneys, and masonry privacy fences was much more common.

4.2 Hurricane Andrew Survey

Table 3 summarizes the key construction characteristics of the sampled homes in the Hurricane Andrew study. Most of the homes were one story in height with nominally reinforced masonry walls, wood-framed gable roofs, and composition shingle roofing.

Table 4 summarizes the key damage statistics determined for the sampled homes in Hurricane Andrew. As expected, the most frequent form of damage was related to windows and roofing with 77 percent of the sampled homes suffering significant damage to roof covering materials. Window damage resulting in at least one broken window was realized in 91 percent of the sampled homes. Blown-off roof sheathing was the most significant aspect of the structural damage with 64 percent of the homes losing one or more roof sheathing panels. Loss of windows and roofing in Hurricane Andrew led to widespread and costly water damage to interiors.

In a similar study of Hurricane Opal, wind speeds ranged from about 44.7 m/s to 51.4 m/s (100 to 115 mph) based on peak gusts at a 10m (33 ft.) height and normalized to open terrain over the sample region. Again, roofing damage was the most common form of wind damage, but at a frequency of only 4 percent of the housing stock [9]. Roof sheathing damage was realized in less than 2 percent of the affected housing stock. This data provides a good contrast to that obtained from the Hurricane Andrew study. Aside from the much lower wind speeds in Hurricane Opal, most of the homes were shielded by trees whereas those in South Florida were in typical suburban residential exposure (wind exposure B) and trees, when present, were denuded in the extreme winds of Andrew. The more extensive damage in Hurricane Opal was caused by storm surge to homes and other buildings on the barrier islands.

Some inferences on the Hurricane Andrew data were found to be statistically significant at a 95 percent confidence level. For example, gable roofed homes suffered significantly higher damage on average than their hip-roofed counterparts with respect to the amount of roof damage realized. It should be noted that this difference in vulnerability is not reflected by commensurate differences in wind loads calculated for roof components in ASCE 7 [10]. Also, two-story homes experienced significantly higher average damage than one-story homes with respect to window and water damage, but not roof damage.

The level of damage to walls was very low with about 2 percent of the homes experiencing some significant form of wall structural damage. About 96 percent of the homes were constructed of nominally reinforced masonry walls (i.e. #4 vertical rebar at 2.4 m (8 feet) on center). Interestingly, this amount of reinforcement falls below the minimum reinforcement ratios that are required in current reinforced masonry or concrete design specifications in the United States. Similarly, roof tie-down failures were reasonably low with 84 percent of the sampled homes experiencing no form of failure to these important elements in high wind regions. About 8 percent of the homes experienced a partial or full roof blow-off failure while most homes had breached envelopes (i.e., broken window glazing and/or a failed garage door) resulting in a higher internal pressure condition according to current design practice represented in ASCE 7.

5.0 STRUCTURAL PERFORMANCE EVALUATION

5.1 Northridge Earthquake

The findings reported herein are summarized from a more thorough evaluation and report on the Northridge Earthquake damage statistics [11]. A total of 49 homes were extracted from the Northridge Earthquake survey discussed previously which met the following criteria:

- one-story, single-family homes;
- stucco exterior wall finish (without structural panel sheathing);
- asphalt composition roof shingles; and
- adequate photographic documentation to characterize the street facing wall configuration.

These criteria resulted in a fairly homogenous, random sample for the purpose of evaluating fundamental relationships between damage and various seismic design factors. The application of findings from this study is limited to the types of homes that meet the above criteria. These homes were of typical construction in the San Fernando Valley with stucco and wood let-in wall bracing. Roughly 80 percent of these homes had crawlspace foundations and 20 percent had slab-on-grade foundations.

Table 5 summarizes the damage to the exterior wall finish of the 49 homes extracted from the survey. The percentages in Table 5 closely coincide to the damage statistics for the complete survey sample of the 341 homes as shown in Table 2.

5.1.1 Solid Wall Ratio (β) vs. Stucco Damage Rating

The value of the solid wall ratio, β, was determined from the photographic documentation of the street-facing side of the sampled houses. It is a simple ratio of the length of solid wall segments (i.e., without openings for windows and doors) to that of the entire wall line. Figure 2 indicates that there is no obvious correlation between the amount of solid stucco wall and the damage rating for the homes in this study. This finding was unexpected. However, there is a possible slight trend when looking at the average β for the NONE and LOW groupings which are 52 percent and 49 percent, respectively. Unfortunately, the variability (scatter) of the data obscures any statistically conclusive finding.

5.1.2 Wall Discontinuities vs. Stucco Damage Rating

Both NEHRP – 97 and UBC – 97 include design provisions for homes constructed with plan irregularities [12][13]. Many of the homes in this study had an *Out-of-Plane Offset* plan structural irregularity. By definition, an out-of-plane offset is a discontinuity in a lateral force resistance path, such as out-of-plane offsets of the vertical elements. This type of irregularity is believed to be associated with substandard performance and current residential construction codes limit a braced wall line offset to 1.2 m (4 ft) for this reason. However, Figure 3 shows no apparent correlation between the number of wall discontinuities on the street facing wall and damage rating for the homes in this study. Figure 4 considers only offsets equal to or greater than 1.2 m (4 ft) as a wall discontinuity. Again, there seems to be no apparent correlation between the stucco damage rating and the number of offsets greater than or equal to 1.2 m (4 ft).

5.1.3 Spectral Response Acceleration vs. Stucco Damage Rating

Data from 9 strong motion stations that recorded ground motions during the Northridge

Earthquake were examined in this study. These 9 stations were in close proximity to the 49 homes investigated in this study. The peak horizontal component for the 0.2 second acceleration response spectra and the 1.0 second acceleration response spectra for 5 percent critical damping were extracted from the data sets for the 9 strong motion ground stations. This data is summarized in Table 6 along with the corresponding return period estimate. The return periods were determined using the U.S. Geological Survey (USGS) hazard curves for each site. The methodology used to create seismic maps and hazard curves is discussed in other reports [14][15].

Ground motion amplification has been observed at the Tarzana – Cedar Hill station in many earthquakes for both strong and weak ground motions. The Tarzana station is located near the crest of a low (20 m) natural hill on the south side of the San Fernando Valley. Topographic effects can explain many features of the observed amplification patterns, but the three dimensional geological structure beneath the hill may also be responsible in part for the very large observed amplification at the top of the hill [16]. For this reason the ground motions at Tarzana were considered anomalous and not used in this study.

The latitude and longitude for each of the 49 houses extracted from the survey were determined. The distance of the homes to the nearest strong motion stations was determined from the latitude and longitude coordinates. The corresponding acceleration response spectra was determined by interpolating between the ground motion stations closest to the house of interest. Figure 5 graphically indicates that there was no apparent correlation between the 0.2 second spectral response acceleration and the stucco damage rating for the sampled homes. Figure 6 suggests that there may be a slight trend between the 1.0 second spectral response acceleration and damage rating on average. The average 1.0 second spectral response acceleration for the NONE and LOW groupings are 40 percent and 46 percent, respectively. It is impractical to consider if the trend is statistically significant since the sample is relatively small and the scatter is relatively large. Although a weakly supported observation, Figure 6 provides an indication that the longer period spectral response acceleration may be the better seismic design parameter for small conventionally built wood-framed buildings such as homes since it appears to better explain the damage.

5.1.4 Case Study – Mecca Avenue

Table 7 summarizes three homes surveyed on Mecca Avenue that were part of the random sample of homes. They were of very similar construction (style) and oriented identically to the ground motion. The three homes summarized in this case study reinforce some of the findings discussed earlier in this paper. The surveyed homes were on the same street and of close proximity to the Tarzana strong motion station. The Tarzana station realized some of the largest ground motion readings during the Northridge Earthquake. In this anecdotal comparison, the damage rating improved with increasing wall discontinuity and decreasing solid wall amount. This finding, though not statistically conclusive, is exactly opposite of conventional engineering theory.

5.2 Hurricane Andrew

The performance of roof sheathing components in Hurricane Andrew was evaluated using principles of engineering and risk modeling and this report summarizes the major findings from the original study [17]. To facilitate the performance evaluation, a Monte Carlo simulation model was developed to predict the frequency of roof sheathing damage (i.e., estimate the percentage of homes experiencing the loss of at least one panel of roof sheathing). The model accounted for variation in sheathing fasteners, construction materials (i.e., framing lumber species and density), South Florida housing characteristics, workmanship effects, and other important parameters affecting the actual sheathing resistance values and wind loads (i.e., surface pressures) experienced. The sheathing pull-off resistance values and variation used in the model were based on tested data with adjustments to account for roof framing lumber used in South Florida [18]. The wind speed over the sample region (Figure 1) was essentially treated as a deterministic parameter and was based on the modeled range of wind speeds experienced over the sample region (i.e., mean = 72.6 m/s (162.5 mph), COV = 0.01). The wind load provisions of ASCE 7 were used to determine wind pressures on the roof sheathing using a suburban exposure, enclosed building internal pressure condition (i.e., applicable to the attic space prior to sheathing loss), and a wind directionality factor of 0.85.

From the statistical damage survey data discussed previously [8], a sub-set of single-story homes with gable roofs and composition shingle roofing was selected as a homogenous sample for the performance evaluation and model calibration. Of these randomly sampled homes, 69 percent±6 percent (95 percent confidence limits) experienced the loss of at least one panel of roof sheathing, and all were in the 71.5-73.8 m/s (160-165 mph)(peak gust) region of Hurricane Andrew as shown in Figure 1.

The key results of the study are the fragility curves shown in Figure 7 which give predictions of the percentage of homes expected to experience the loss of one or more panels of roof sheathing based on the hurricane magnitude (wind speed). Figure 7 contains four different fragility curves representing different levels of roof sheathing attachment. The curve representing the actual housing population (second from the top) is calibrated to the actual observed roof sheathing damage frequency of 69 percent±6 percent (95 percent confidence limits) at a wind speed of 72.4 m/s (162 mph) (peak gust) with a mix of 6d and 8d sheathing nails representing roof sheathing attachments in the modeled housing population. The model prediction is 71 percent -- tending toward a slight over-estimation of the actual damage frequency.

Some very interesting findings are drawn from the analysis:

- Actual Performance Better Than Minimum Code

The minimum requirement for roof sheathing attachment in the 1991 South Florida Building Code was 6d common nails spaced at 30 cm (12 in) on center in the field of the roof sheathing panels (see top curve in Figure 7) [19]. If this minimum requirement was representative of the entire housing population, the predicted frequency of roof sheathing loss would have been about 92 percent instead of 69 percent of the homes. One may conclude that this minimum code requirement was very insufficient for the South Florida wind climate and that the housing performance was actually better than that implied by the code minimum. However, neither the code-implied performance nor the actual performance is considered acceptable.

- Revised Code Minimum Will Significantly Improve Performance

The next most important observation is that the level of performance expected for new homes constructed under the 1994 South Florida Building Code will be significantly improved (bottom curve in Figure 7) [20]. This improvement is primarily attributed to increasing the roof sheathing attachment requirement to 8d common nails from 6d common nails without any change in workmanship or inspection that may result in improved installation quality. Decreasing the spacing to 15 cm (6 in) on center and requiring sheathing attached to the gable end framing to be nailed at 10 cm (4 in) on center are also important features in the new code. New homes constructed under this revised code provision are predicted to perform with a roof sheathing loss frequency of about 1 percent in the next event equivalent to Hurricane Andrew.

- Benchmark for Acceptable Performance

An acceptable roof sheathing damage frequency may be targeted at about 10 percent of the homes for an event the magnitude of Hurricane Andrew in the South Florida wind climate (see lower box in Figure 7 at 72.4 m/s (162 mph) wind speed). This target is risk-consistent with the generally acceptable performance of standard roof sheathing attachments in typical extra-tropical wind climates covering most of the non-coastal United States. Thus, a damage frequency of about 10 percent of the homes losing one or more panels of roof sheathing in an event similar to Hurricane Andrew constitutes a respectable goal or target performance for the South Florida housing population. Obviously, the actual frequency of roof sheathing damage (i.e., 64 percent of the all SFD homes) does not meet the proposed benchmark for acceptable performance.

Though not similarly evaluated, the incidence of building collapse (wall racking) or roof blow-off should have a lower target damage frequency because of the more severe consequences. Indeed, the occurrence of this type of damage was documented at a reasonably low level in Hurricane Andrew – 2 percent for wall damage and 8 percent for roof-wall connection damage [8]. (The 2 percent wall damage statistic is primarily associated with wood frame wall construction which comprised about 4 percent of the sampled homes). Of the nominally reinforced masonry homes sampled, no wall failures were documented; extremely rare incidences of severe masonry wall damage, however, were found in the housing population [8].

- Possible Wind Directionality and Shielding Effects

One point of concern following the generation of the fragility curves was related to the level of damage at lower wind conditions. According to the wind map in Figure 1, the maximum wind speeds for Hurricane Andrew were less than about 62.6 m/s (140 mph) for areas north of 88th Street (Kendall Ave.). Kendall Avenue was the northern boundary for the statistical sampling region in the HUD damage survey [8]. This northern boundary of the 'damage zone' was selected because of the lack of any significant damage, particularly roof sheathing loss, proceeding further northward.

As shown in Figure 7, the calibrated MCS model predicts damage frequencies of more than 50 percent at the 62.6 m/s (140 mph) wind speed. One possible reason is that the rate of wind speed decrease in Figure 1 is too low north of the eyewall of Hurricane Andrew (i.e., an error in the hurricane wind field model). This would require that the wind speeds drop from 71.5 m/s (160 mph) to less than about 44.7 m/s (100 mph) at the crossing of Kendall Avenue to agree with a damage level well below 10 percent based on observation in this region (see Figure 7). This wind-speed drop-off may be physically unreasonable, though not implausible. Therefore, it is believed that this drop-off in actual damage relative to the modeled damage is at least in part due to a change in the wind exposure condition (exposure B was used in the model). This change in wind exposure is attributable to two characteristics. First, the areas north of Kendall Avenue were generally older developments with more mature trees which could have shielded the lower buildings (i.e., one-story homes). Second, the wind speeds in this region were low enough that the trees were able to maintain some level of protection during the hurricane without being completely destroyed or denuded. It is also possible that the generally older homes in this region were built using materials and methods that were somewhat more wind resistant.

To test this hypothesis, the MCS model was re-run at the 62.6 m/s (140 mph) wind speed with an additional adjustment to account for possible shielding effects due to the survival of the trees. The calculated wind loads were reduced by 25 percent for shielding which corresponds with the results of a recent wind tunnel study of low-rise structures in a densely built-up (i.e., shielded), exposure B environment [21]. With this adjustment, the MCS model predicted a roof sheathing damage frequency of about 1 percent which agrees reasonably well with the anecdotal observation of very little structural damage north of Kendall Avenue. Thus, the existence of mature trees in a relatively dense mix with development may reduce wind damage significantly, provided the wind speeds do not exceed the ability of the trees to act as barriers.

Some of this disparity may be attributed to an unaccounted increase in wind directionality effect not considered in the model. Proceeding north of the hurricane eyewall, the wind speed magnitude and range of wind directions experienced are both diminished. Thus, a wind directionality factor of 0.75 (as applicable to extra-tropical wind conditions) may be appropriate as concluded in an extensive analytical wind tunnel study [21].

It is probable that the following factors all contributed to an apparent over-prediction of damage north of the eyewall (outside of the statistical damage study region):

- wind field modeling errors,
- increased reductions in wind load associated with wind directionality,
- increased shielding associated with the survival of trees; and,
- differences in the construction materials and methods used in the generally older homes located north of the eyewall and the sample study region.

6.0 CONCLUSIONS

6.1 General

1. It is feasible and economical to obtain reliable and representative data on housing construction and damage frequencies (i.e., performance) following extreme natural events such as earthquakes and hurricanes.

2. Construction and performance data collected and evaluated as described in this paper may be used to rationally assess performance, identify need for improvement, evaluate the adequacy of engineering methods relative to actual performance, and develop cost-effective solutions related to the real problems associated with natural hazards.

6.2 Northridge Earthquake

1. The single-family housing population performed reasonably well in the Northridge Earthquake with 95.9 percent of the sampled homes receiving a stucco damage rating of NONE or LOW; very few homes exhibited significant structural damage related to life-safety concerns.
2. Despite fundamental structural performance relationships assumed in conventional seismic design practices and theory, there was no obvious or significant correlation between solid wall ratio or spectral response acceleration and the damage rating for the statistically representative sample of homes examined in this study.
3. The findings provide some indication that the long period (1 second) spectral response acceleration is the preferable ground motion parameter for design of small, light-frame structures.
4. This study also confirms that certain irregularities, such as wall out-of-plane offsets, do not have the affect on performance implied by current design and construction provisions.

6.3 Hurricane Andrew

1. Given the magnitude of Hurricane Andrew, the structural (life-safety) performance of the typical South Florida housing stock (i.e., masonry walls with wood frame roofs) was found to be very reasonable with the prominent exception of roof sheathing attachment.

2. Wind loads determined in accordance with ASCE 7 provide a reasonable basis to assess the actual performance of residential roof components given the use of an "enclosed building" internal pressure condition for the determination of roof sheathing loads, the use of a 0.85 wind directionality factor, and appropriate consideration of wind shielding effects.

3. The actual performance of the housing stock was, on average, better than that implied by the governing building code provisions preceding Hurricane Andrew's devastation – though both are considered unacceptable.

4. Revisions to the South Florida Building Code (SFBC) following Hurricane Andrew resulted in roof sheathing attachment provisions that are slightly conservative, but practical and effective.

5. The statistical data on roof-to-wall connection performance in Hurricane Andrew gives ample evidence that the roof tie-down connection (as required by SFBC and executed in practice) was reasonably reliable.

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[21] Ho, Tat Chiu Eric, *Variability of Low Building Wind Loads*, Ph.D. Thesis, Department of Civil Engineering, The University of Western Ontario, July 1992.

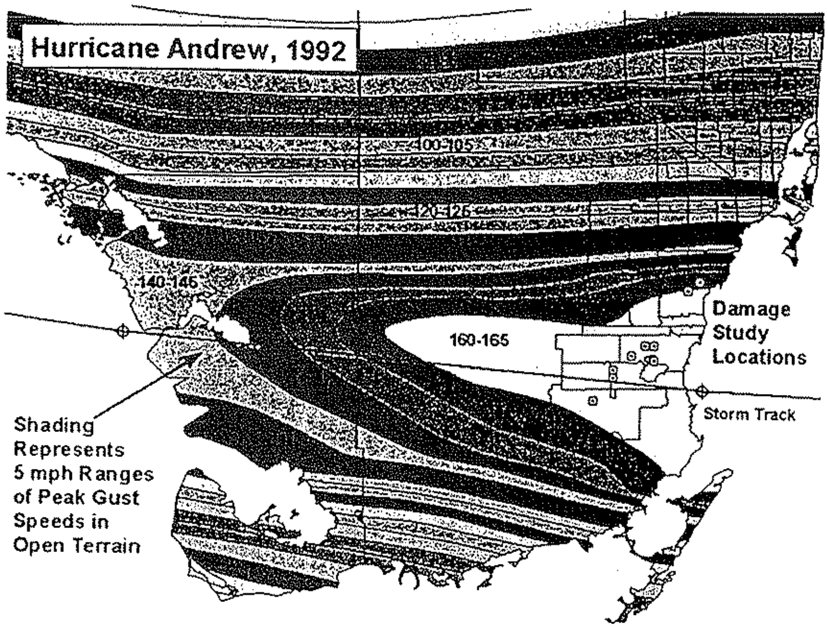

Figure 1
Maximum 3-Second Gust Wind Speeds (mph)
Experienced in Hurricane Andrew at 10 m (33 ft) Elevation over Open Terrain
(Courtesy Applied Research Associates, Raleigh, NC)
1 mph = 0.447 m/s

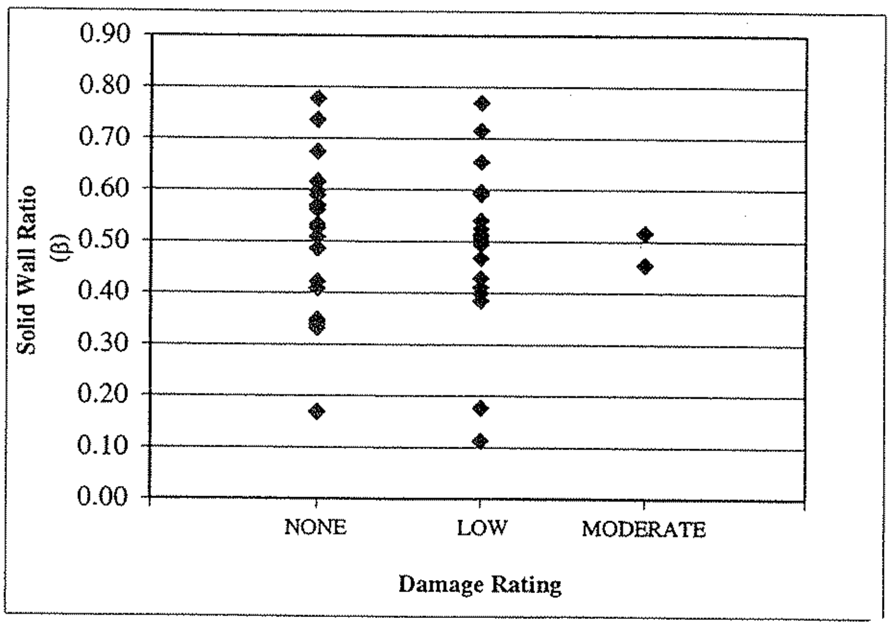

Figure 2
Solid Wall Ratio (β) vs. Damage Rating
(Data Points Represent Individual House Samples)

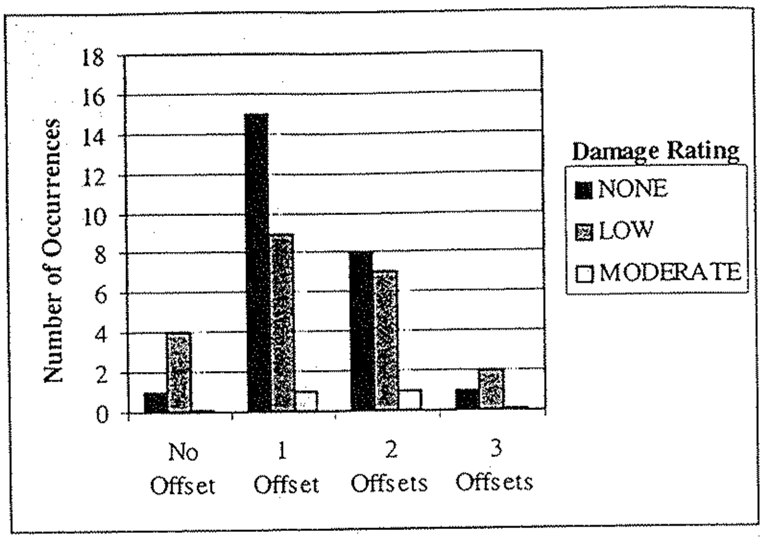

Figure 3
Non-Correlation of Wall Offsets and Damage Rating

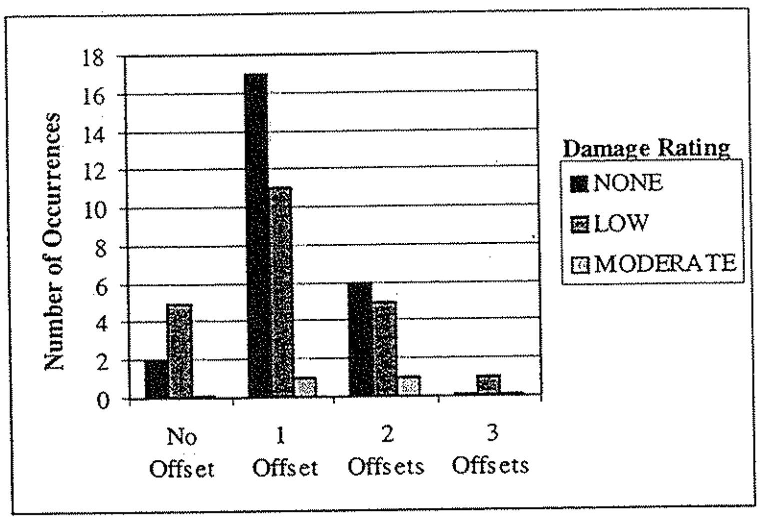

Figure 4
Non-Correlation of Wall Offsets Greater than 1.2 m (4 ft) and Damage Rating

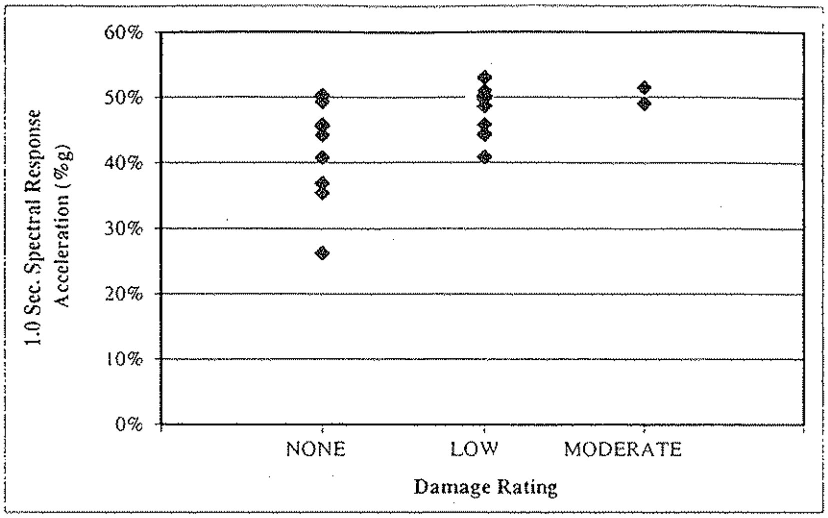

Figure 5
0.2 Sec Acceleration Response Spectra vs. Damage Rating
(Data Points Represent Individual House Samples)

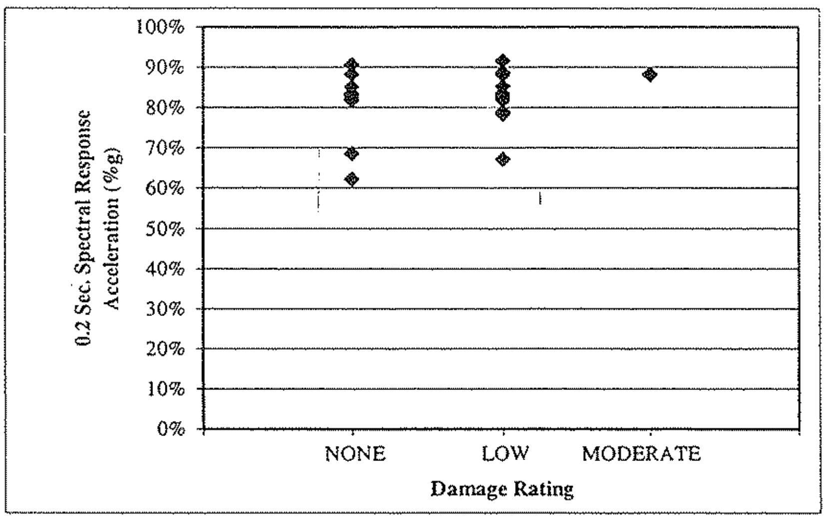

Figure 6
1.0 Sec Acceleration Response Spectra vs. Damage Rating
(Data Points Represent Individual House Samples)

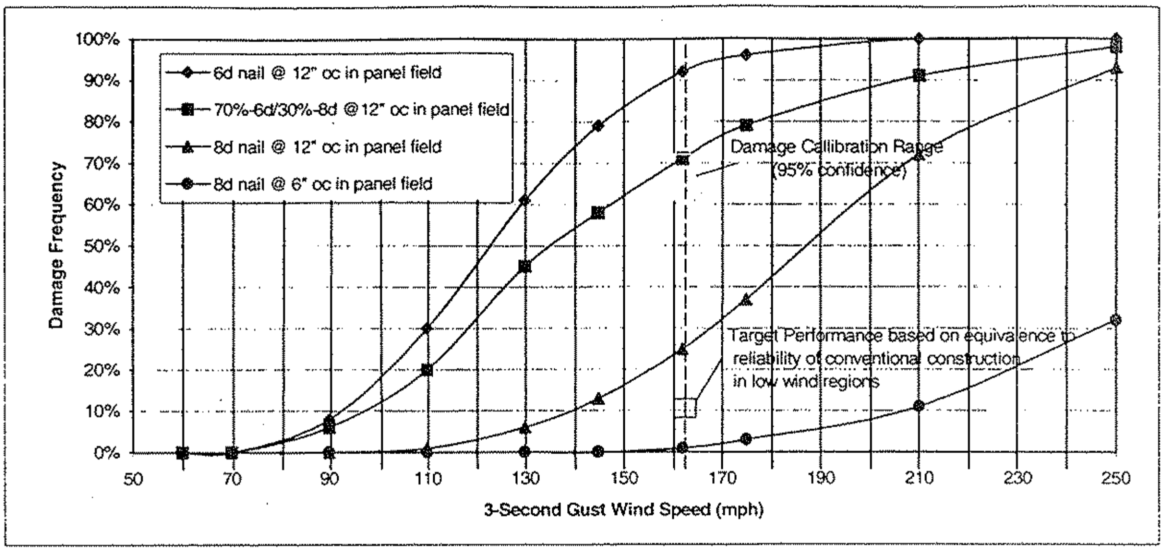

Figure 7
Roof Sheathing Fragility Curves
for One-Story Homes in a Suburban Exposure
(1 mph = 0.447 m/s).

Table 1
Construction Characteristics of SFD Dwellings

COMPONENT	NORTHRIDGE HOMES, 1994
Number of Stories	79% One 18% Two 3% Other
Wall Sheathing	80% None 7% Plywood 13% Unknown
Foundation Type	68% Crawlspace 34% Slab 8% Other
Exterior Finish	50% Stucco/Mix 45% Stucco Only 6% Other
Interior Finish	60% Plaster 26% Gypsum Board 14% Other/Unknown

Table 2
Description of Damage to Single-Family Detached Homes
(Northridge Earthquake)

Observed Damage	Sample Size	No Damage	Low Damage	Moderate Damage	High Damage
Foundation	327	295	26	3	3
Foundation-to-Walls	324	293	24	5	2
Walls	317	311	6	0	0
Roof	328	326	2	0	0
Exterior Finish	306	155	141	9	1
Interior Finish	265	132	122	11	0
Estimated Damage within Survey Area		No Damage	Low Damage	Moderate Damage	High Damage
Foundation		87.9% < **90.2%** < 92.5%	5.9% < **8.0%** < 10.0%	0.3% < **0.9%** < 2.7%	0.3% < **0.9%** < 2.7%
Foundation-to-Walls		88.1% < **90.4%** < 92.7%	5.4% < **7.4%** < 9.4%	0.5% < **1.5%** < 3.6%	0.2% < **0.6%** < 2.2%
Walls		94.0% < **98.1%** < 99.0%	0.9% < **1.9%** < 4.1%	0.0% < **0.0%** < 0.9%	0.0% < **0.0%** < 0.9%
Roof		97.2% < **99.4%** < 99.6%	0.2% < **0.6%** < 2.2%	0.0% < **0.0%** < 0.9%	0.0% < **0.0%** < 0.9%
Exterior Finish		46.7% < **50.7%** < 54.7%	42.1% < **46.1%** < 50.1%	1.6% < **2.9%** < 5.5%	0.1% < **0.3%** < 1.8%
Interior Finish		45.5% < **49.8%** < 54.1%	41.8% < **46.0%** < 50.3%	2.4% < **4.2%** < 7.3%	0.0% < **0.0%** < 1.1%
Foundation		161,300 < **165,600** < 169,800	10,700 < **14,600** < 18,400	600 < **1,700** < 4,900	600 < **1,700** < 4,900
Foundation-to-Walls		161,800 < **166,000** < 170,200	9,900 < **13,600** < 17,300	900 < **2,800** < 6,500	400 < **1,100** < 4,100
Walls		172,600 < **180,000** < 181,700	1,600 < **3,500** < 7,500	0 < **0** < 1,700	0 < **0** < 1,700
Roof		178,400 < **182,400** < 182,700	300 < **1,100** < 4,000	0 < **0** < 1,700	0 < **0** < 1,700
Exterior Finish		85,600 < **93,000** < 100,300	77,200 < **84,600** < 91,900	2,900 < **5,400** < 10,100	100 < **600** < 3,300
Interior Finish		83,500 < **91,400** < 99,300	76,600 < **84,500** < 92,400	4,300 < **7,600** < 13,400	0 < **0** < 2,100

Table 3
Construction Characteristics of Sampled Single-Family Detached Homes

Component	Hurricane Andrew 1992
No. of Stories	80% One 2% Other 18% Two
Roof Construction	81% Gable 6% Other 13% Hip
Wall Construction	96% Masonry 4% Wood Frame
Foundation Type	100% Slab
Siding Material	94% Stucco 6% Other
Roofing Material	73% Comp. Shingle 18% Tile 9% Other
Interior Finish	Primarily Gypsum Board

Table 4
Percentage of Sampled Single-Family Detached Homes With 'Moderate' or 'High' Damage Ratings

Component	Hurricane Andrew 1992
Roof Sheathing	24% (64%)[*]
Walls	2%
Foundation	0%
Roof Covering	77% (99%)[1]
Interior Finish (water damage)	85%

[1]Percentage in parenthesis includes "low" damage rating and, therefore, corresponds to homes with one or more sheathing panels lost or any form of roof covering damage. Other values indicate moderate or high damage ratings, including roof blow-off or similar serious failures (i.e., collapse).

Table 5
Summary of Exterior Finish Wall Damage to the Sub-Sample of 49 Homes

Damage Rating	Percent of Survey
NONE	55.1
LOW	40.8
MODERATE	4.1
HIGH	0.0

Table 6
Summary of Strong Ground Motion Stations in Close Proximity to the Sampled Homes

Station Name	Latitude	Longitude	0.2 sec Spectral Response Acceleration (%g)	0.2 sec Return Period (yrs)	1.0 sec Spectral Response Acceleration (%g)	1.0 sec Return Period (yrs)
Century City - LACC Nth	34.064	118.417	88%	292	43%	432
LA - UCLA Grounds	34.068	118.439	90%	301	24%	196
LA - Hollywood Storage Lot	34.090	118.339	100%	281	46%	514
Tarzana - Cedar Hill	34.160	118.534	270%	13,619	79%	1,813
Arleta - Nordhoff Station	34.236	118.439	81%	169	53%	502
Pacoima - Kagel & Canyon	34.288	118.375	76%	116	53%	326
Malibu - Point Dume	34.013	118.800	26%	139	10%	209
Moorrpark - Fire Station	34.288	118.881	63%	108	23%	99
Newhall - Fire Station	34.387	118.530	140%	268	117%	3,021

Table 7
Summary of Homes Surveyed on Mecca Avenue

Address	Solid Wall Ratio, β	No. of Wall Offsets	Closest Station	Damage Rating
#1 Mecca Ave	0.349	2	Tarzana[1]	None
#2 Mecca Ave	0.389	0	Tarzana[1]	Low
#3 Mecca Ave	0.455	0	Tarzana[1]	Moderate

[1]The strong motion readings at the Tarzana ground station were among the largest recorded during the Northridge Earthquake.