Modeling of Hurricane Damage for Hawaii Residential Construction

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Abstract

Past information on Hurricane Iniki damage to Hawaii buildings of residential, commercial, and resort occupancies has been gathered and geo-referenced on GIS. Comprehensive reconstruction cost documentation has been combined with post-hurricane aerial photography and linked to a robust property tax database of construction type attributes and property valuation. Using the data available in the property tax records to define construction attributes, residential building fragilities and loss functions have been developed along with risk relativity factors. *The resultant Damage Curves estimate hurricane damage to a wide variety of Hawaii building types as a function of peak gust windspeed.*

Keywords: Hurricane; Building Damage; GIS; Hawaii

1. Introduction

Past information on wind damage to buildings of residential, commercial, and resort occupancies has been gathered and geo-referenced on GIS. These reconstruction cost estimates have then been combined with post-hurricane aerial photography imaging and robust databases of construction type, foundation, age, and roof design parameters. The wind speed-up results were used with a hurricane windfield model developed by a concurrent project, *Wind Speed Mapping of Hawaii and Pacific Insular States by Monte Carlo Simulation*, and a topographic effects model developed earlier in this project [1] to define wind speed regions of Hurricane Iniki to further segregate the data. Multivariate regressions of wind speed-defined building inventories subsequently were performed to develop building fragility, risk relativity, and expected wind loss functions for prototypical buildings reflecting the performance of Hawaii-specific construction features.

2. Hurricane Iniki

Hurricane Iniki was the most destructive storm to hit Hawaii in recorded history. The system initially formed from tropical depression 18E on September 5, 1992 near 12° N, 135° W. On

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September 7 at 5pm, it was upgraded to Tropical Storm Iniki near 12° N, 144.5° W. Iniki followed a westward track embedded in an easterly flow along the southern edge of the seasonal subtropical high pressure ridge that historically had carried most hurricanes south of the Hawaiian Islands. Iniki became a hurricane with estimated central pressure of 992 mb on September 8 at 11pm Hawaii Standard Time when its position was at 13° N 152° W, and soon began translating west-northwest (See Figure 1).

On September 10, as Iniki approached the weakening western edge of the subtropical high pressure ridge, a large low pressure area at 30° N and cold trough located east of the International Dateline created southwesterly upper level flow and southerly low level flow. As a result, when located near 15° N 159° W Iniki started to "recurve" northward while continuing to intensify (951 mb). At 2:00 pm Thursday afternoon, September 10, 1992, the National Weather Service had issued a bulletin indicating that Iniki would bypass the Hawaiian Islands. However, by 5:30 pm, a Hurricane Watch was issued for Kaua'i with the center of the storm near 16° N 160° W. At 8:30 pm, a Hurricane Warning was issued for Kaua'i. Located 210 km south-southwest of Lihue, Kaua'i on September 11, at 11am, Iniki's central barometric pressure of 938 mb was the lowest ever recorded in a central Pacific hurricane, and Iniki was classified as a Category 4 hurricane with flight-level sustained winds of 65 m/s (145 mph) and gusts of 78 m/s (175 mph).

The hurricane made landfall at 3:30 pm Hawaii Standard Time at Category 3 to 4 intensity (945 to 950 mb) and quickly passed over the island by 4:10 pm (See Figure 2). Iniki was a relatively small and compact storm with a radius to maximum winds of about 15 km, with sustained winds in open terrain of approximately 55 m/s (125 mph) and peak gusts of 72 m/s (160 mph) or more, subject to further increases caused by topographic speed-up. The peak gusts of 64 m/s (143 mph) recorded at Makahuena Point, located at the southeast corner of the island about 20 km distant from the center of the storm, and 58 m/s (130 mph) recorded at Lihue, about 25 km from the center, are considered representative surface windspeeds at landfall to the east of the eyewall in the right forward quadrant of the hurricane, that are also relatively free of major topographic effects [2].

3. Damage Data and Analysis

The investigation initially obtained available data from NOAA Storm Data reports [3], American Red Cross surveys [4], FEMA damage/claim databases, State Civil Defense data on building damage, State hurricane impact economic reports, Structural Engineers Association of Hawaii, and National Research Council and National Science Foundation studies [5], the Kaua'i County permit database for post-hurricane reconstruction, and insurance bureau information, including a risk-based premium rate study [6]. Hurricane Iniki (September, 1992) winds have previously been qualitatively interpreted and wind directionality vectors mapped by T. Fujita [7] based on low-level aerial photography taken by Air Survey Hawaii [8]. The raw photographs were acquired for several flight lines and geo-referenced so that building damage could be examined at a similar scale of consideration as the wind-tunnel test. NASA ER-2 high-altitude photographs from the post-Iniki missions were also examined and found to be less suitable because of high cloud cover, and photographic enlargement of the original negatives would be required to develop these images at the proper scale for scanning and insertion into GIS. The low-level photographs were relatively cloud-free, and they were at a scale and size that was more workable, while retaining adequate resolution for examination of individual structures on parcels. The communities of Kilauea, Princeville, Hanalei, and Wainiha, which experienced greater levels of damage, lie within the measured region of the Kaua'i model. Puhi, Lihue, Kapaia, and the Kapaa, Kealia regions have the mildest amount of topographic/terrain features. These areas were more reflective of Kaua'i building baseline performance with less influence of topographic wind-speed effects.

Comprehensive building damage data based on post-Iniki reconstruction permit applications and inspections had been input into a database by the former Office of Emergency Permitting (OEP), which was temporarily established by FEMA after Hurricane Iniki. However, the original data had not been maintained for several years, and some commentary data fields and linked secondary tables were corrupted and no longer exportable from a legacy hardware and software platform. Nevertheless, after significant efforts, the major portion of the master database for the entire island of Kaua'i was eventually converted to a present day database application file, and these 22,000+ permit records were analyzed and sorted to obtain more accurate information on the level of damage and costs (i.e., the permitted dollar value of building repair, reconstruction, and/or demolition).

Pertinent data fields of this special hurricane reconstruction database included, among other information: Tax Map Key Code or TMK, a unique identification coding for each property in Hawaii; Land Use Zonation; Structure Number or Unit Number; Type of Permit; Post-Hurricane Damage Tagging; Description of Structure; Roof Repairs; Roof Structure Repairs; Wall Repairs; Whether 50% Damaged or Greater, any Demolition; Whether Rebuilt; Estimated Value of Permitted Work; Permit Date.

Extensive data processing tasks related to the sorting and analysis of this data included:

- elimination of void and superseded permits,
- elimination of permits for detached temporary housing,
- assembling residential, single-family structure records from parcels across a variety of land use zonings,
- identification of multiple, detached structures, each with a different damage state, on a single parcel,
- identification of multiple separated structures with identical damage states on single parcels,
- separation of principal structures from minor structures such as detached carports and sheds,
- multiple-unit buildings such as condominiums, timeshares, and hotels where the total project's reconstruction permit value is assigned to a single unit record or to a single building in a complex,
- location of damage zones within separate multiple-unit buildings within a single parcel,
- correction of miscoded OEP TMK and Tax database fields
- matching of initial demolition costs with reconstruction costs of the later work permit,
- destroyed structures identified with a demolition permit which were not subsequently rebuilt,
- aggregation of cumulative-cost data from several permits issued for a structure, and identification of its highest damage state,
- aggregation of the tax assessments of several buildings of like occupancies on a single parcel,
- quality control checks utilizing random sample queries of third-party tax record information for verification of available data for area, year built date, use (specific occupancy), structural material, and tax valuation,

- additional data screening performed as a part of the quality control of data to eliminate outlier entries in the tax records, and
- accounting for a lack of complete documentation of reconstruction, resulting in a number of structures without definitive damage assessment or reconstruction estimated values.

In addressing this last item, other data fields were first used to determine the best match of damage characteristics to place these structures in the appropriate categories. For example, matching permits for temporary, detached shelters would indicate loss of roof. Permits for certain types of nonstructural work only would indicate water damage without structural damage. The OEP also performed field tagging of structures that exhibited damage expected to need structural repairs. Residences without structural damage could also be exempted from most permitting requirements after a verifying inspection by the Office of Emergency Permitting. A table of post-hurricane field inspection logs was utilized to clarify the status of properties without subsequent building permits.

Database tables of Tax Map Key (TMK) indexed site locations sorted by various damage levels were geocoded onto GIS, for geographic comparison at parcel-level resolution with matching aerial photographs of the north coast region of Kaua'i. This GIS overlay provided a means verifying damage states for individual properties lacking detailed building permit or precise field tagging inspection information. To prorate the correct proportion of remaining single-family, resort/multi-family, commercial and other occupancy parcels where the damage data was incomplete, random samples were taken for detailed aerial photograph assessment for parcel damage identification. Querying of available field inspection records was used to select the parcels actually needing clarification of damage states. Random numbers were assigned to this group of TMK records and a sample was selected by sorting of the random numbers. The number of samples was determined to yield a 99% confidence level of no more than a 10% error in the determined proportion of damage states of single-family residences. For other occupancies, a 90% confidence level of no more than a 5% error was used. Damage categorization of the randomly selected sites was then performed by individual inspection of aerial photography. The proportions thus determined were used to distribute the larger population of sites lacking detailed, building-permit data.

The reconstruction permit database table was then linked to the Kaua'i tax assessor files of 1994 vintage. The 1994 tax files were used to be consistent with the Iniki building inventory. The linked building permit and tax-record database included over 20,000 structures. Data fields most pertinent to this study include:

TMK	Tax Map Key Parcel Identification Code
Building Number	Structure number within the parcel
Building Value	At the time of reconstruction or repair permit
Area	Building area in square feet
Roof Design Configuration	Flat, Gable, Hip, Shed, Gambrel, Other
Roof Structural Material	Wood, Steel, Concrete
Roofing Material	Built Up Roofing & Composition, Tile, Shingle, Shake, Metal
Number of Stories	1, 2, or more
Wall Construction Type	"Single wall" wood, "Double wall" wood, Masonry, Steel
Foundation	Wood piers, Stone, Masonry, Concrete

Year Built Original and/or "Effective" based on improvements/additions

Table 1 shows the average proportions of construction attributes found for Kaua'i single-family residences at the time of Hurricane Iniki. Based on property tax records, at the time of Hurricane Iniki single-family residential houses were about equally divided on Kaua'i between wood "single-wall" (45%) and wood "double-wall" construction (55%), with a very small minority of homes built with masonry walls. Significant variations from this average profile were found in each community region of Kaua'i.

Single-wall construction utilizes flat tongue and groove boards placed vertically to form a load-bearing exterior wall without studs. A flat, wood top plate is attached against the vertical siding board to serve as a "supporting" ledger for the roof rafter, and the board is nailed at the bottom to a rim joist and sill beam, transferring its load through vertical shear (see Figure 3). These connections are typically of minimal uplift capacity. Roof construction in single-wall residences is typically light non-engineered framing with composition shingles on tongue and groove (T & G) wood decking, or corrugated metal deck roofing directly attached to rafters. Full plywood sheathing is not provided, and rafters are spaced about four feet apart in the T & G roofed systems. This type of construction is no longer permitted in new construction, but it developed a significant portion of the housing stock due to its low cost and the absence of thermal insulation requirements in Hawaii. Since single-wall construction is less substantial and more vulnerable to wind damage, their proportion was expected to be very significant to hurricane-loss estimation. These proportions differ significantly from island to island in Hawaii and between regions on each island, depending on the development history of a particular community.

"Double-wall" refers to conventional modern wood frame construction utilizing load-bearing studs and wall sheathing. In a portion of recent (~pre 1990) double-wall construction, full plywood sheathing is not provided. Shakes and tiles on wood furring strips over rafters with or without roof structural sheathing also commonly occur.

It should be noted that Kaua'i residential construction was not upgraded after Hurricane Iwa (1982); the normal permitting process was totally waived for post-Hurricane Iwa reconstruction, and so repairs did not significantly improve the pre-Iwa building stock. By accounts of structural engineers, the predominant reconstruction practice after Hurricane Iwa was to replace "in-kind" without conformance to code standards. The construction quality of the post-Iwa repairs and reconstruction would not be expected to perform at par with typical code-compliant construction. There were no requirements for hurricane roof to wall uplift ties for new single family residential construction until the 1989 Kaua'i County Building Code adoption of the 1985 UBC.

The Uniform Building Code Appendix 2518 for Conventional Light-Frame Construction in High-Wind Areas, specifying a complete load path for nominal uplift resistance, was required for *new* single-family residential construction subsequent to the post-Iniki 1992 Kaua'i Building Code adoption of the 1991 UBC. However, a presumption that all Kaua'i residential construction was subsequently upgraded after Hurricane Iniki (1992) would not be valid. 60% of the housing stock did not suffer significant roofing loss during Iniki, and therefore, would not have hurricane clips added in repairs. Although UBC Appendix Section 2518 was incorporated for new construction in 1992, in 1993 the County of Kaua'i decided to allow nonconforming buildings to be rebuilt to their condition *prior* to Iniki, and allowed replacement single-wall construction and replacement corrugated metal roofing without any plywood sheathing underlayment. Therefore, only new single-family residential building stock constructed in Kaua'i from 1992 to the present day would have greater hurricane resistance commensurate with the provisions of the above-referenced UBC high wind provisions.

Based on analysis of the occupancy categories and population of each within the above communities, buildings were grouped into regions of sufficient inventory size to maintain robustness of descriptive statistics of the damage data. GIS geocoding of parcel TMK identifications allowed parcels to be grouped by query into the mutually exclusive topographic regions according to geographically assigned boundaries.

Within each region, the single-family residential structures, multi-family and multi-unit residential structures, and commercial structures were segregated. Then, the permit records of demolition and reconstruction were separated within each occupancy classification. The reconstruction permit records were subsequently sorted into mutually exclusive damage level groupings based on the OEP scope of repair and damage severity rating. Each individual parcel was then categorized based on its most severe damage state (there can be a successive number of permits issued for a property, as well as multiple structures on a parcel). Figure 4 shows an example of damage state mapping by property parcel for a portion of the region of Hanalei. The permit-reconstruction cost values are used to calculate dollar losses for each structure on each parcel. The costs of demolition of damaged portions of structures are also included in the total-damage estimates. These damage estimates were then converted to individual damage ratios using the total-building value and individual repair costs per square foot using the building-area information from the linked tax assessor file. This normalized the OEP-estimated value of reconstruction to an equivalent "damage" ratio and "damage cost" per square foot of structure area. Overall damage statistics for an example region is given in Table 2 for single-family homes.

The Kaua'i data suggested that significant residential damage occurred prior to roof structural damage, about 25% of the tax assessor's valuation of the residence. Roof damage generally occurred in association with loss ratios of 50% of the tax-assessed value. The damage cost at an OEP estimated level of 50% or greater damage with some demolition was often actually greater than the tax assessor's valuation of the residence. It appeared that the damage ratios determined by reconstruction cost submitted in building permits indicated damage severities appeared similar (but somewhat less severe) relative to the reports from initial Red Cross sidewalk surveys of the exteriors of structures.

The average extended time required for substantial completion of repairs and reconstruction is also presented. The extended time involves the total process of assessing damage, clean up, determining necessary work, obtaining funding, and construction. This was done by individually tracking for each structure the dates of the initial building permits and subsequent permits for work of more secondary nature. The average extended times are not strongly related to the level of damage; this may be due to the limited resources available to island communities after a major disaster involving a large proportion of the building inventory, i.e., demand surge.

TABLE 1 – Kaua'i Principal Building Attribute Profiles – 1993

Wall and Foundation Construction	Stories	Roof Design	Roof Material	Incidence
Single Wall on Piers	1	Hip	Metal	14.8%
Single Wall on Piers	1	Gable	Metal	8.3%
Single Wall on Slab	1	Gable	Composition or Shake/Shingle	7.1%
Single Wall on Piers	1	Hip	Composition or Shake/Shingle	4.7%
Single Wall on Slab	1	Hip	Metal	4.7%
Single Wall on Slab	1	Hip	Composition or Shake/Shingle	4.6%
Double Wall on Slab	1	Gable	Composition or Shake/Shingle	13.7%
Double Wall on Slab	1	Hip	Composition or Shake/Shingle	12.7%
Double Wall on Piers	1	Gable	Composition or Shake/Shingle	5.4%
Double Wall on Slab	2	Gable	Composition or Shake/Shingle	2.2%
Double Wall on Slab	2	Hip	Composition or Shake/Shingle	1.9%
All others				19.9%

Note: Masonry wall construction is very uncommon in single family residences, much less than 1%

Wall Construction Combinations	
Double Wall 1-story	45%
Double Wall 2-story	6%
Single wall on Wood Piers	28%
Single wall on Concrete or Masonry	21%

Roofing Material	
Built-up or Composition	51%
Shake or Shingle	17%
Metal Roofs	29%
Tile	3%

Roof Design	
Hip Roofs	46%
Gable Roofs	51%
Others	3%

Pre-1994 Age Distribution	
Pre-1970	31%
1971-1982	36%
1983-1993	33%

Table 2 - Damage Loss and Distribution Data Summary for the Kaua'i North Region

<u>Hurricane Iniki Damage to Single-Family Residential Structures</u>

Damage State	Total Listings	Percentag e	Average Permitted Reconstruction Cost (1994 $)	Average 1994 Building Valuation	Average % Damage (Cost/ Tax Valuation)	Average Living Area (sq. ft.)	Average Cost of Direct Damage/Sq. Ft.	Extended Time for Substantial Repair (months)
No Damage / Minor Damage	1039	53.6%	n/a	$180,580	n/a	1,663	≈**$2**	N/a
No Roof Repairs & < 50% Damage	70	3.6%	$22,710	$124,960	**22%**	1,686	**$18**	**14**
Roof Repairs & < 50% Damage	554	28.6%	$39,930	$138,500	**54%**	1,568	**$33**	**13**
≥50% Damage or Rebuild	150	7.8%	$66,580	$189,460	≈40%	1,746	≈$40	**17**
Demolition & ≥ 50% Damage or Rebuild	105	5.4%	$109,590	$149,520	**90%**	1,239	**$112**	**15**
Complete Demolition without Rebuild	20	1.0%	(Demolition only) $11,260	$149,860	**108%**	1,525	**$106**	**10**
Totals / Average	1938	100%		$165,230		1,620	**$21**	**14**

4. Effect of Certain Residential Construction Attributes

Prior to multivariate inferential statistical analysis of the data, descriptive statistics were developed of the parameters of relevance to fragility curves for the Hawaii building stock, such as:

Damage by Wall Construction

Damage by Roof Material

Damage by Roofing Material and by Wall Construction

Damage by Roof Design

Damage by Roof Design and by Wall Construction

Damage by Roof Design, by Roofing Material, and by Wall Construction

Damage by Age, by Wall Construction, and by Roof Design;

Damage by Foundation by Wall Construction

Damage by Height

Damage by Height and by Wall Construction

For the purposes of this paper, selected statistics on damage states are shown aggregated in Table 3 into larger categories of damaged and severely (≥ 50%) damaged structures. The Kaua'i data shows that single-wall construction had 50% greater incidence of significant damage, and more than 200% greater "failure" rate than double wall as measured by the 50% damage threshold. Damage ratios were about 10%- to 20% higher, and overall repair costs were $20 more for single wall construction than for double wall.

Metal roofs performed poorly relative to all other types of roofing for single wall dwellings. For double wall construction, metal roofs was a secondary factor, reflecting that more modern engineered metal roof systems are different than the antiquated corrugated sheet type used on single wall homes. Attention to the attachment detail for a modern raised-seam metal roof has resulted in improved hurricane resistance [9]. Tile roofs performed significantly better than all others in limiting the incidence of severe damage. There is an interesting comparison to the tile construction failures seen in Hurricane Andrew, Florida (1992) [10 and 11]. Clay and concrete tiles in Hawaii were predominately attached with nailing to wood furring strips, which were in turn nailed to rafters; in Florida, tiles were often laid on a mortar pat on a full plywood sheathing underlayment

Wind-tunnel tests of roof pressure coefficients for low-rise structures, observational reports by Hawaii structural engineers on gable roof *failure modes*, and typical insurance rating systems deem gable roofs a much higher risk than hip roofs [12]. However, unlike Hurricane Andrew, analysis of the Hurricane Iniki damage data does not indicate any statistically significant difference in the failure *rate* of these two predominant types of residential roofs. Prior to Hurricane Iniki, neither gable nor hip roofs would have had roof to wall hurricane ties, and so resistance to uplift would have been deficient in either roof design configuration. Also, in single-wall construction with gable roofs, the exterior wallboard would structurally span full-height to the top edge of roof. Rose [13] attributed the somewhat better than expected performance of the double-wall gable roofs in Kaua'i to the likely presence of blocked roof sheathing diaphragms and lateral bracing of the gable-end roof trusses.

Table 3 - Effect of Certain Construction Attributes of Detached Single Family Housing		n_i in group	Group % of the total number of structures	n_i' damaged structures	% damaged within n_i structures in group	Average % repair cost for damaged structures	Average $ repair cost per square ft for damaged structures	Number severely damaged structures (those with ≥50% loss)	% of severely damaged within n_i structures in group	Conditional % of severely damaged within $n_{i'}$ damaged structures in group	Ave. % loss for severely damaged structures	Average loss/sq ft for severely damaged structures (>= 50% damage)
Wall	*single*	3856	48%	2302	60%	60%	$55	699	18%	30%	83%	$100
	double	4187	52%	1645	40%	44%	$39	349	8%	21%	69%	$75
Roofing	*metal*	2299	29%	1408	61%	65%	$61	524	23%	37%	84%	$101
	others	5577	71%	2474	45%	50%	$45	522	9%	21%	85%	$102
Roof-by Single Wall	*gable*	1917	53%	1069	56%	60%	$59	342	18%	32%	84%	$105
	hip	1744	48%	1113	64%	61%	$51	323	19%	29%	82%	$94
Roof by Double Wall	*gable*	2109	54%	864	41%	48%	$41	187	9%	22%	70%	$77
	hip	1789	46%	644	36%	39%	$35	115	6%	18%	70%	$68
Age by Single Wall w/ metal roof	*Pre-1970*	1421	38%	948	67%	68%	$65	393	28%	42%	84%	$102
	≥1970	491	13%	282	57%	61%	$52	60	12%	21%	95%	$110
Age by Double Wall w/o tile roofs	*Pre-1983*	1539	39%	749	49%	49%	$39	170	11%	23%	67%	$75
	≥ 1983	2267	57%	765	34%	39%	$37	136	6%	18%	62%	$85

Kaua'i Aggregate	8078		3958	49%	57%	$54	1049	13%	27%	87%	$108

It outwardly appeared that damage was affected by the age of residential structures. Single-family residences reflected an overall failure rate indicating a relative risk of major structural failure that increased for every decade of building age. When the data were examined within wall construction and roofing combinations, the effect of age itself was separated from the age-related autocorrelations with the evolution of construction practices from single-wall, metal-roofed structures highly prevalent prior to 1970, the roughly equivalent proportions of single and double wall construction with greater use of composition shingles in the 1970's, and the phasing out of single-wall construction in the 1980's. Once this was done, age was more precisely indicated to be a significant factor for single-wall and for double-wall homes, relating to particular trends of construction technique and code requirements, respectively.

The number of stories for either type of wall construction had a negative correlation with damage cost, and positive for incidence of damage. This appears to result from the effect of the second story's protection of the first story and the dispersion of square footage into a lesser proportion directly under roof, as opposed to the 100% exposure of a single story home to roof damage.

An earlier insurance rate study by the Hawaii Hurricane Relied Fund [6] made several simplifying assumptions, which resulted in some inaccuracies in reported loss statistics used for establishing premium structures. It did not consider any parcels that contained more than one structure, and so properties with multiple single-family homes were excluded. It assumed that a demolition permit implied that the entire structure was demolished, rather than as sometimes indicating a portion; for the fragility of roofing systems and materials. It did not include the structures that only required roof repairs, only those with a demolition permit (about 70% associated with 50% of more damage, and about 25% associated with demolished structures). The demolition permit group in the 1996 study was a significantly smaller number of single-family houses, not at all correlated to those needing roof repairs with less than 50% damage. Also, the HHRF study apparently included damaged structures logged in with damage but no structural reconstruction permit, as being undamaged. Being concerned about single-family residential hurricane insurance, it did not consider the commercial sector or the resort, timeshare, or multi-family (apartment/condominium) sector of the damaged structure inventory.

5. Building Damage Fragility, Loss, and Damage Functions

The project created a study of the Hurricane Iniki storm scenario deriving wind speeds including topographic effects. Time histories of wind-speed data for an array of 272 locations covering the island were produced using the hurricane windfield model from a concurrent affiliated project, *Wind Speed Mapping of Hawaii and Pacific Insular States by Monte Carlo Simulation*. Results corresponding to the site peak gust wind-speed maxima were then contoured. Figure 5 is an example map of the topographic alteration of peak gust windspeed for the Hanalei region on the North coast of Kaua'i. Using GIS, the geocoded building inventory was further categorized by estimated Hurricane Iniki windspeed. Multivariate analysis of damage and loss to Kaua'i single-family residential buildings of various construction types was performed for the Iniki database including the windspeed variable. Figure 6 illustrates the process used in developing each function and its relationship to the Damage Functions.

Fragilities, or the probabilities of states of damage, were determined through a two –step logistic multivariate regression for each wind zone and for the entire inventory. First, the dependent variable logarithm of the ratio of probabilities of roof or greater damage versus no substantial damage was determined. Then, the data subset of structures with roof or greater damage was analyzed by the second stage logistic regression to determine the probabilities of more than 50% total damage versus roof damage with less than 50% total damage. Accordingly, probabilities, P_i , for each of three damage states (none or minor, roof but less than 50% total damage, and greater than 50% damage or demolition) were evaluated based on the significant independent variables associated (for alpha of 5%) with each type of construction, for each category of windpeed.

The procedure utilizes iterations of coefficient estimation and residual tests, to converge on the combination of parameters that maximizes the likelihood of obtaining the frequencies of each damage state. The outcome variable, $\hat{Y}$, is the probability of having one damage outcome or another based on a nonlinear function of the best linear combination of predictors; with two outcomes:

$$\hat{Y}_i = \frac{e^u}{1+e^u}$$

where $\hat{Y}_i$ is the estimated probability that the ith case ($I = 1, \ldots, n$) is in one of the damage state categories and u is a form of linear regression equation of categorical independent variables:

$$u = A + B_j X_j + \ldots + B_k X_k$$

with constant A, coefficients $B_{j,}$, and predictors, X_j for k predictors ($j = 1, 2, \ldots, k$)

The *logit* or log of the odds creates a linear regression equation for a non-linear equation for $\hat{Y}$:

$$\ln (\hat{Y} / 1\text{-}\hat{Y}) = A + \sum B_j X_{ij}$$

This linear regression is the natural log ($\log_e$) of the probability of being in one group divided by the probability of being in the other group. The procedure for estimating coefficients is maximum likelihood. Maximum likelihood estimation is an iterative procedure that starts with arbitrary values of coefficients and determines the direction and size of change in the coefficients that will maximize the likelihood of obtaining the observed frequencies. Then residuals are tested and another extrapolation of direction and size of change in coefficients is made, repeatedly, until the coefficients converge.

Loss Functions were developed by linear multivariate regression utilizing the three-outcome damage state as an independent categorical variable together with the construction attribute set of parameters (Table 4). An alpha significance of 10% was used for this series of regressions. Loss functions for outcome variables of % of building tax value and $ per square foot were determined independently. In general, % loss regressions had better fit to the data than $/sf. However, the $/sf loss functions provide a useful calibration between the two principal types of Hawaii construction of single and double wall construction (the later costing about 70% more than the former).

Expected Losses in % and $/sf, were then calculated for each windspeed regime by the summation of fragilities (probabilities of damage $\text{states}_{windspeed}$) * $\text{losses}_{\text{damage state}}$. By normalizing with respect to a baseline construction type, wind risk relativity tables are developed to provide the relative loss multipliers for all construction variations (significant or not) in the Hawaii building stock. The normalization baseline utilized is the double wall, single-story, home on concrete foundation with shingle, shake, or tile roofing, and either a hip or gable roof configuration, built after 1990 and valued at about $144/sf in 1994 dollars. This type of construction is prototypical of a conventional wood-frame home built with hurricane ties at the rafter to wood wall connection.

Table 4 Summary of Linear Regression Variables for % Loss and $(1993)/sf Loss by Damage State by Construction Categories

<table>
<tr><td>Damage State</td><td colspan="2">3: No Roof</td><td colspan="2">2 Damage < 50%</td><td colspan="3">1: Damage ≥ 50%</td></tr>
<tr><td>Wall Construction</td><td>Single Wall</td><td colspan="2">Single Wall</td><td colspan="2">Double Wall</td><td colspan="2">Double Wall</td></tr>
<tr><td>Height</td><td>Single Story</td><td colspan="2">≥ 2 stories</td><td colspan="2">Single Story</td><td colspan="2">≥ 2 stories</td></tr>
<tr><td>Windspeed</td><td colspan="7">Windspeed Categories</td></tr>
<tr><td>Roofing System</td><td colspan="2">Metal</td><td colspan="2">BUR or Composition</td><td colspan="3">Shingles, Shakes, or Tiles</td></tr>
<tr><td>Building Tax</td><td colspan="2">< $50K</td><td colspan="2">$50K to $100K</td><td colspan="3">>$100K</td></tr>
<tr><td>Age Splits</td><td>Pre-1970</td><td colspan="2">1970 & later</td><td>Pre-1983</td><td colspan="2">1983-1989</td><td>1990-1992</td></tr>
<tr><td>Foundation</td><td colspan="3">Concrete Slab or Conc/Masonry Wall</td><td colspan="4">Elevated on Posts/Piers</td></tr>
<tr><td>Roof Design</td><td colspan="3">Hip</td><td colspan="4">Gable</td></tr>
<tr><td>Loss Outcomes</td><td colspan="3">% of Building Tax Value</td><td colspan="4">$/square foot</td></tr>
</table>

Damage Functions, expressing the % loss by windspeed, were then developed from the baseline % Loss Function adjusted for each possible combination of construction attributes by the risk relativities for the two windspeed regimes. Because of the large number of possible combinations of construction features and the high potential significance on performance (there are about 340 potential combinations affecting fragility and about 340 combinations affecting the loss functions), the use of a baseline Damage Function backbone was highly advantaged since it is easier to use and more accommodative than a series of individual Damage Functions for selected building types. Damage Functions are shown in Figure 7 for a *few* Hawaii building types with comparisons to FEMA 55, the *Coastal Construction Manual* [14]. Note that the Damage Functions were based on reconstruction costs, *not* insurance payouts; for example, losses of more than 50% were not transformed to a 100% (full) loss. This limited illustration is not meant to be used as representative of typical Hawaii construction for property hurricane insurance purposes.

A significant advantage of the Damage Functions is their basis on information typically kept in property tax assessor files. Therefore, the necessary housing inventory database for each island exists, and data acquisition does not need to include labor-intensive field surveys. The veracity of the existing single-family housing property tax records for Hawaii and Maui Counties was verified in 1999 and 2000 studies conducted for the Hawaii State Earthquake Advisory Committee (Department of Defense) by Insurance Services Office of Hawaii, Inc.

6. Conclusions

Past information on wind damage to buildings of residential, commercial, and resort occupancies has been gathered and geo-referenced on GIS, combining post-hurricane aerial photography imaging with robust property tax databases of construction type, foundation, age, and roof design parameters with reconstruction cost estimates. This information also provided documentation on the time period required for rebuilding after Hurricane Iniki, which should be considered in estimating direct economic loss impacts in island locations. Using data available in property tax records to define construction attributes Residential Building Fragilities, Loss, and Damage Curves have been developed along with Risk Relativity Factors that permit a wide variety of endemic Hawaii building types to be evaluated as a function of peak gust windspeed. The project also provided GIS-based micro-zoning of wind amplification (described in paper [1]), including topographic effects, and then determined the loss performance of a wide variety of prototypical building types characteristic of Hawaii. The distribution of development and spatial variability of wind speed-up effect in the study region strongly suggests that loss-estimation methodologies in areas with similar complexity of topography need to utilize a more detailed geographic resolution of building inventory database.

Acknowledgements

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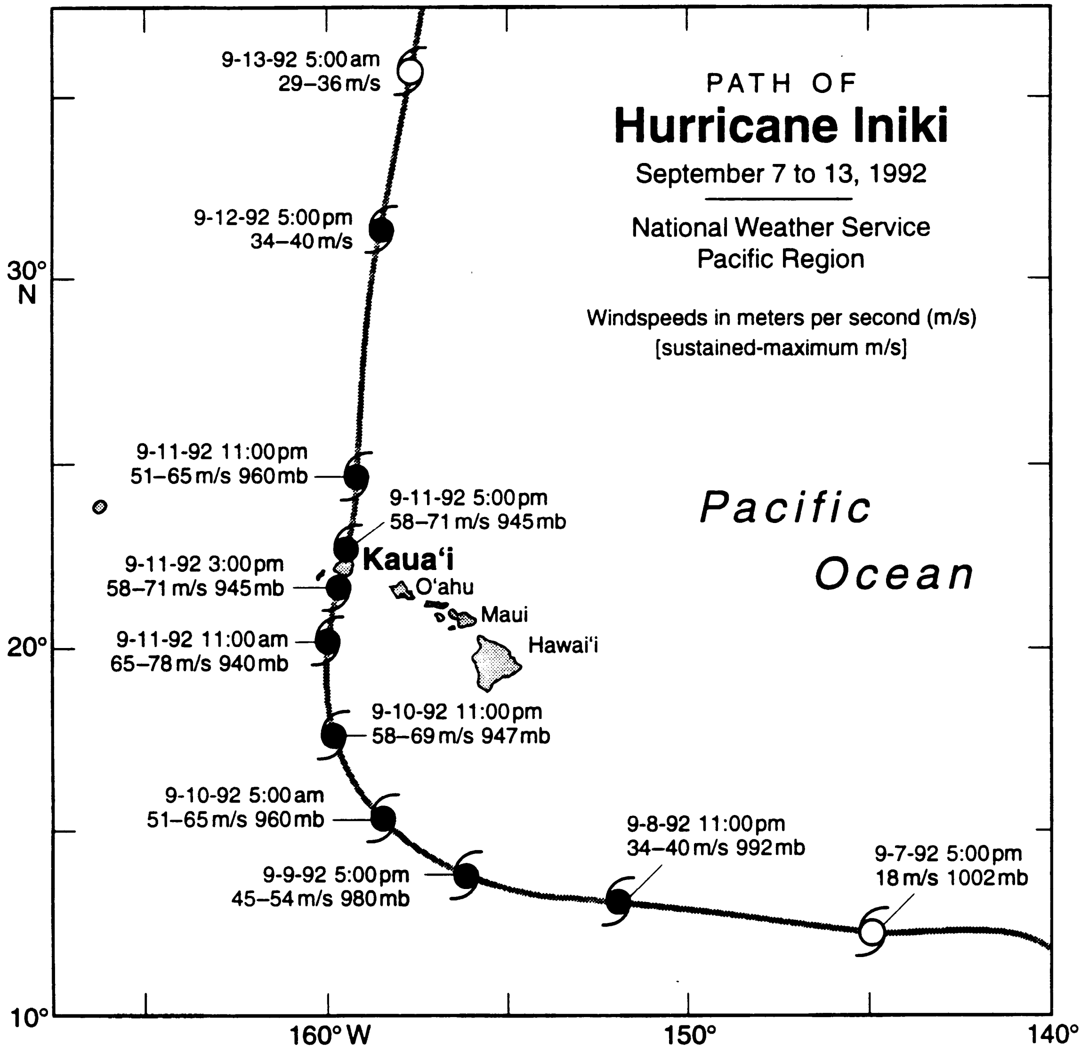

Figure 1 – Path of Hurricane Iniki, 1992 (National Weather Service)

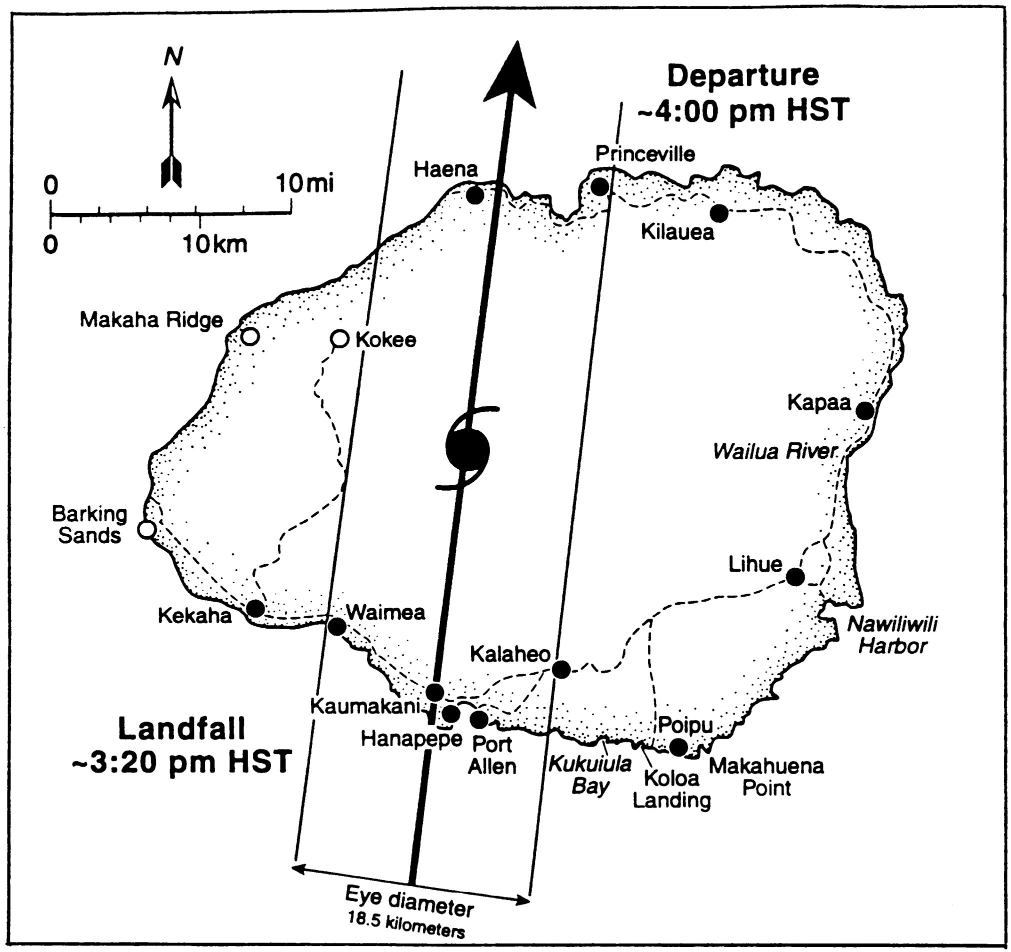

Figure 2 – Detailed Track of Hurricane Iniki at Landfall

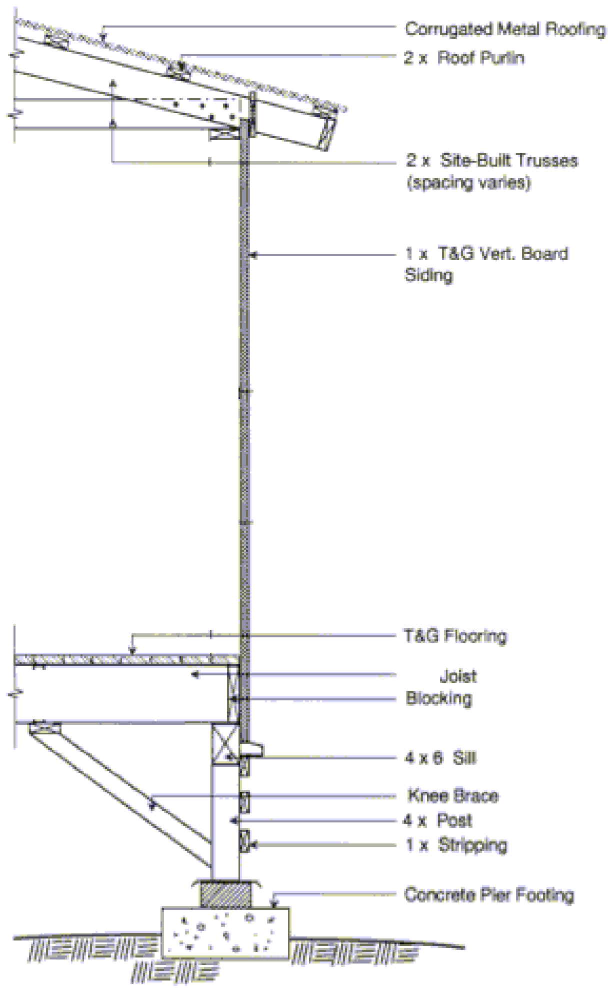

Figure 3 – An Example of one Style of Historic Hawaii Single-Wall Construction

(note that there are many variations from the style shown in this illustration)

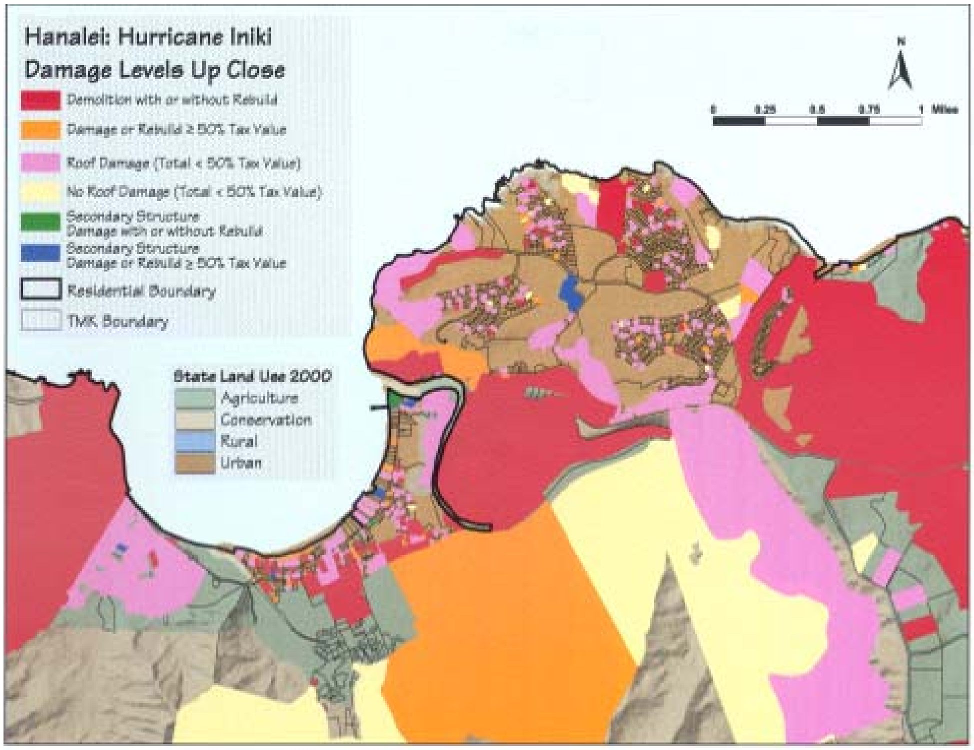

Figure 4 – A Detailed Wind Damage State Map by Property Parcel for Hanalei and Princeville

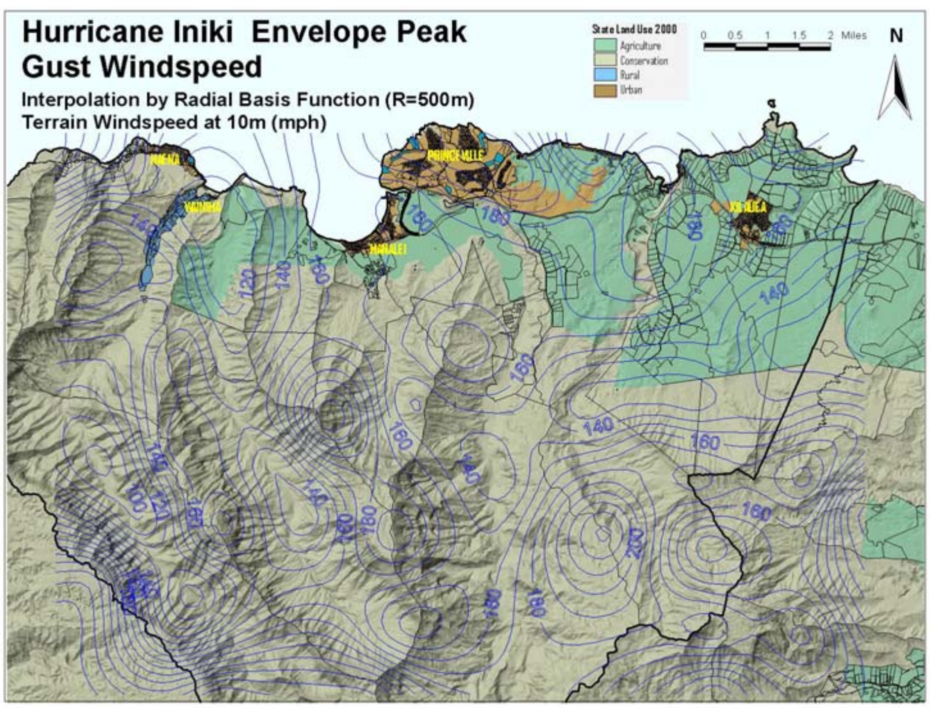

Figure 5 – A Wind Speed Map for Hurricane Iniki including topographic speed-up –the North Coast of Kauai including Hanalei and Princeville

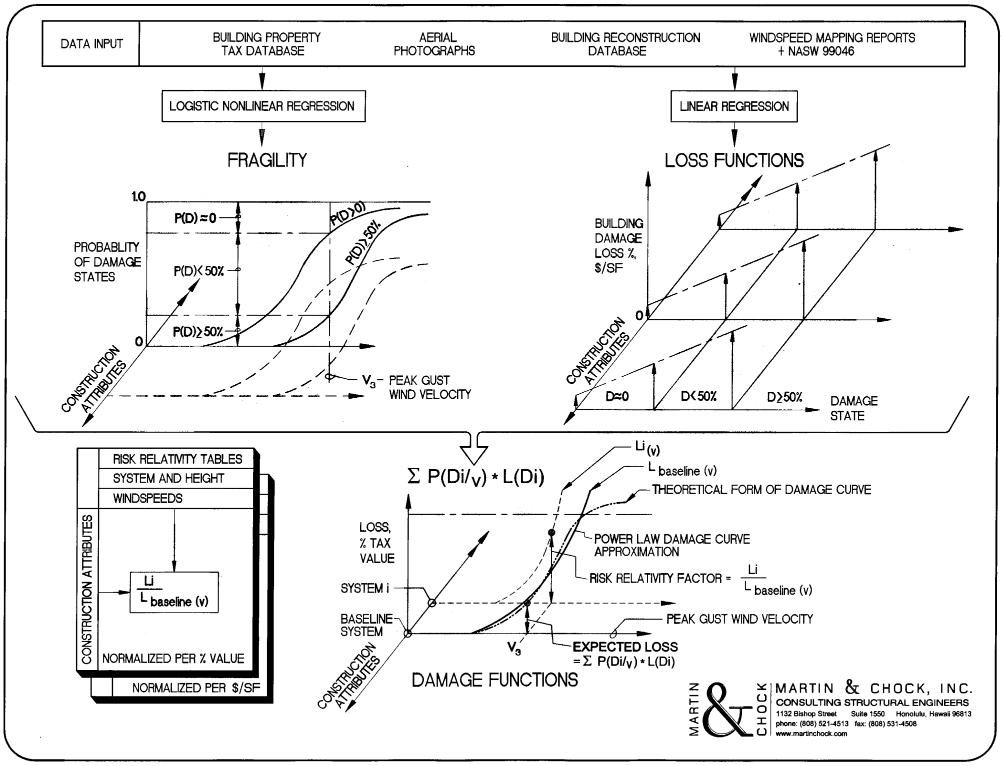

Figure 6 – ***Development of Fragility, Loss, Damage Functions, and Risk Relativites***

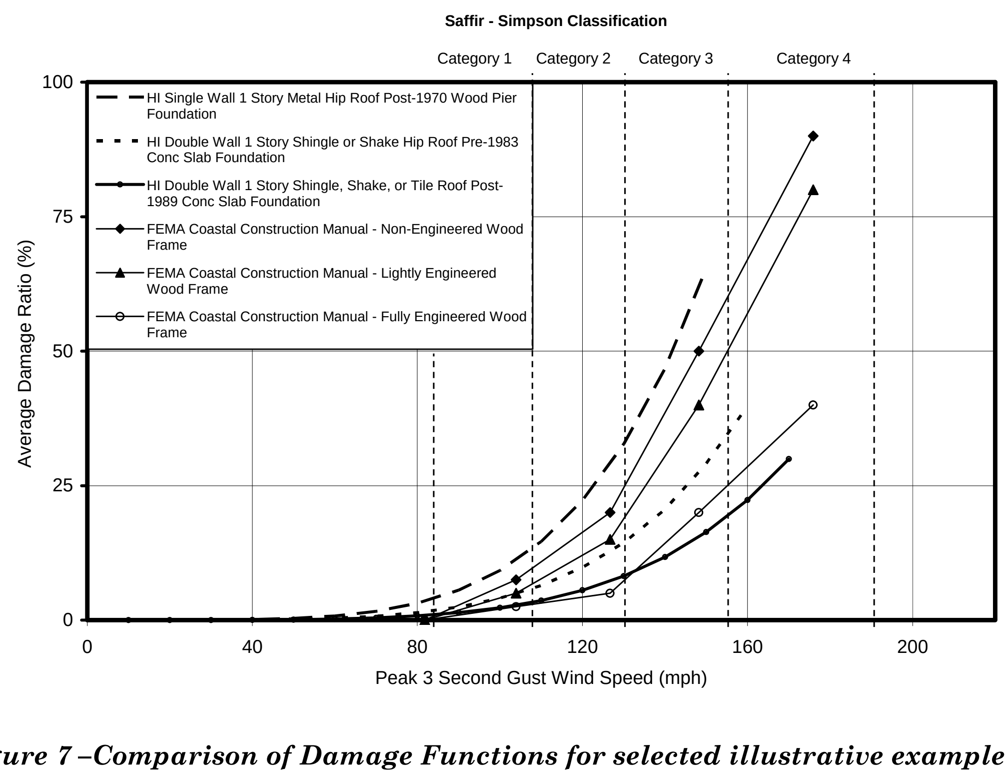

Figure 7 –Comparison of Damage Functions for selected illustrative example cases