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Assessment and quantification of hurricane induced damage to houses

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Abstract. Significant costs to the public and private sectors due to recent extreme wind events have motivated the need for systematic post-hurricane damage data collection and analysis. Current post disaster data are collected by many different interested groups such as government agencies, voluntary disaster relief agencies, representatives of media companies, academicians and companies in the private sector. Each group has an interest in a particular type of data. However, members of each group collect data using different techniques. This disparity in data is not conducive to quantifying damage data and, therefore, inhibits the statistical and spatial description of damage and comparisons of damage among different extreme wind events. The data collection does not allow comparisons of data or results of analyses within a group and also prohibits comparison of damage data and information among different groups. Typically, analyses of data from a given event lead to different conclusions depending upon the definition of damage used by individual investigators and the type of data collected making it difficult for members of groups to compare the results of their analyses with a common language and basis. A formal method of data collection and analysis-within any single group-would allow comparisons to be made among different individuals, hazardous events and eventually among different groups, thus facilitating the management and reduction of damage due to future disasters.

This research introduces a definition of damage to single family dwellings, and a common method of data collection and analysis suited for groups interested in regional characterization of damage. The current state-of-data is presented and a method for data collection is recommended based on these existing data collection methods. A fixed-scale damage index is proposed to consider the damage to a dwelling's features. Finally, the damage index is applied to three dwellings damaged by Hurricane Iniki (1992). The damage index reflects the reduced functionality of a structure as a single family detached dwelling and provides a means to evaluate regional damage due to a single event or to compare damage due to events of different severity. Evaluation of the damage index and the data available support recommendations for future data collection efforts.

Key words: condition assessment; damage index; data collection; damage difinition; structure functionality; Hurricane Iniki; post-hurricane damage assessment; extreme-wind.

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1. Introduction

The weekly cost for structural damage caused by natural hazards in the United States (such as earthquakes, floods, severe winds and wildfires) is estimated to be US$1 billion (SNDR, 1996). Most of the losses associated with these events were not insured, placing a significant strain on private and public response and recovery resources. Since 1989, over US$43 billion has been paid in property and casualty (P/C) insurance claims for the ten events that have been the most costly to the P/C insurance industry. Six of these ten events were related to severe wind storms and resulted in P/C insurance claims exceeding US$26 billion. Claims resulting from Hurricane Andrew (1992) alone reached US$15.50 billion (PCS 1997)[1]. The increase in population and number of dwellings in areas prone to hurricanes and the business practices of insurance prior to 1992 resulted in State Farm Fire and Casualty Company (the largest property insurer in the US) experiencing total claims following Hurricane Andrew that exceeded its collective operating margin for the preceding 50 years (Chiu and Chock 1998). These figures illustrate the significant cost of hurricanes to the private and public sectors. Improved procedures to document hurricane damage will complement the existing qualitative strategies for damage documentation moving towards providing a better quantitative characterization of wind-induced damage. The new documentation procedures will, in particular, extend the current practice by providing a methodology to systematically quantify and map the spatial distribution of damage. Also, better data collection and analysis procedures would contribute to improved benefit-cost analyses used in the development of risk management strategies for mitigating future hurricane damage.

A consistent description of hurricane damage to houses needs to be established so that comparisons of damage can be made among houses and among different events. However, data collection is often uncoordinated among all interested groups and even within a particular group (e.g., government agencies, engineers, financial companies, etc.). Data collection efforts following a hurricane are often difficult as communities are left dysfunctional and without basic services by the event. Post-disaster data collection becomes a tedious enterprise associated with unfavorable conditions such as a hot and humid climate, lack of power and communication networks, and hostile residents and bureaucrats. In general, there is an air of confusion amongst the residents, emergency response personnel and those involved in post-disaster studies. Emergency recovery efforts focus on providing a community's residents with basic housing, food and utilities, with few resources being expended on the collection of perishable data that provide a quantitative spatial and temporal indication of damage or a measure of loss. As a result, there is little consistency in the evaluation of damaged structures, even by personnel whose tasks include placing a cost on the amount of damage that a community has experienced. Because a formal definition of damage does not exist, most engineering related post-disaster studies have focused typically on subjective descriptions of damage, and concluded with general statements of the hazard's magnitude, the state of -and compliance with -local building codes, and the typical building practice in the area. While qualitative studies provide valuable descriptions about the ability of structures to resist wind loads, they do not make it possible to relate the damage from one

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[1] Due to variable bookkeeping methods, the figures reported by the insurance industry may include costs in addition to those incurred by structural damage.

event to another.

While damage data are available from a number of events (Hurricanes Alicia, Andrew, Opal and Iniki, for example), the collection methods and data collected have been uncoordinated and in some cases random, thereby preventing the consistent description and quantification of damage. Therefore, estimating the benefits and costs of damage mitigation and risk management strategies for future hurricane events is difficult, as is developing rational risk mitigation plans that utilize information based on historical data. Consistent characterizations and documentation of damage would allow quantitative analysis for studying the percentage of dwellings damaged, the different levels of damage that houses experienced, and the spatial distribution of the damage.

Ultimately, a consistent procedure for post-hurricane condition assessment will allow :

- cost estimates of events to be compared among different events,
- information about favorable and unfavorable construction practices to be documented quantitatively;
- improvement of risk management strategies by clarifying acceptable risk levels;
- regional loss estimation procedures to be more consistent; and
- different interest groups to compare damage data.

The impetus for this research is the need to define hurricane induced damage to single family dwellings, document damage that results from hurricanes in a systematic manner and provide a framework that will allow damage to be compared among a population of houses or series of events. The objective of this paper is to present a damage index for single family timber dwellings that is based on systematic post-hurricane data collection. The methodology is presented and subsequently applied to three houses damaged by Hurricane Iniki. The scope of this paper is to propose a methodology that will provide consistent measures of damage based upon data collected in the field.

2. Overview of current data collection methods

A user group initiates development of a hurricane damage mitigation framework by establishing levels of acceptable risk (the probability of loss that is acceptable within a specified time) and then developing mechanisms to reduce potential losses to the desired probability. Because the built environment has been constructed to resist natural hazard induced loads that have a defined probability of occurrence (a probability exists that the loads will be exceeded with consequences that are not well defined). For example, current building criteria in the US specify a single hazard level and infer a performance level for some natural hazards (flood, earthquake, wind and snow) as shown in Table 1. These single performance objective criteria were the basis for most of the existing built environment and, therefore, behavior of structural systems is not well understood when the specified hazard levels are exceeded. Establishing multiple levels of hazard and performance would quantitatively express levels of acceptable risk for serviceability and strength in design procedures and allow targets to be established for mitigation strategies.

In addition to defining acceptable risks, creating an effective mitigation strategy requires that damage resulting from events be documented and quantified in order to evaluate the ability of the existing built environment to resist different hazard levels. To characterize the

Table 1 Natural hazards and associated performance criteria in the United States

Hazard	Probability of Exceedance	Return Period	Performance Level
Earthquake	0.10 in 50 years	475 years	Collapse Prevention
Flood	0.39 in 50 years	100 years	Minimal/moderate damage
Snow	0.64 in 50 years	50 years	No damage
Wind	0.64 in 50 years	50 years	No/minimal damage

Table 2 US stakeholders interested in hurricane induced damage and related data

Stakeholder	Type of Constituency	Typical Damage Data Collected
Insurance Company	Private Business	Claims paid to policy holders
Federal Emergency Management Association (FEMA)	Government Agency	Subjective damage data
Red Cross	Non Government Organization	Houses damaged, number of persons in public shelters
National Association of Home Builders	Non Government Organization	Number of houses damaged, subjective descriptions of damage
Engineers	Professional	Subjective descriptions of damage

vulnerability of the existing built environment, damage needs to be defined in a manner that can be documented and quantified so that consistent comparisons can be made of damage that resulted due to historical events. While it is beyond the scope of this paper to formulate a hurricane damage mitigation strategy, a method for long-term damage-data collection is presented here beginning with a review of the current data collection procedures.

Post-disaster data are collected by many different stakeholders including government agencies, non-governmental organizations, private business concerns and academic researchers. Stakeholders collect data that are of particular interest to their work or constituents. Table 2 provides some examples of persons interested in post-disaster information and the type of data they collect. Table 2 lists the predominant stakeholders in the United States, while most countries have parallel stakeholders. Obviously, the vastly different interests of the various parties require each to collect data of interest to that particular stakeholder. Ideally, a constituency would have a common language and method to document damage. Unfortunately, most individual companies or organizations collect damage data in a manner suitable only to that entity. For example, insurance companies have individual claims processing forms and procedures, and methods of documenting how much a company paid for different types of damage. Procedures also vary across insurance companies. Similarly, engineers have been collecting damage data for many years; however, the data usually consist of descriptions of damage to individual facilities. While these studies have provided valuable lessons regarding the mechanisms of failure under wind loading, a method to collect and quantify damage is necessary to describe the losses statistically; for example, the number of houses that incurred different percentages of damage. The following sections discuss the established methods of collecting damage data and introduce a new data collection method that provides data for a damage quantification algorithm.

2.1. Data collection methods

Because of the different needs of various users, data collection methods and the type of data collected vary among groups. This situation hinders attempts to share information for decision making purposes or damage analysis. Yet, data collection methods can be generally categorized into five categories:

1. Independent data collection by various parties
2. Forms developed to collect similar data
3. Software data requirements
4. Building permit information
5. Insurance claim forms

Table 3 presents some measures of loss or damage and identifies the user group with whom the loss is most closely associated. Also, each of the data collection methods is described below.

2.1.1. Independent damage documentation

Independent data collection consists of the documentation of damage to individual facilities by a person or team of persons. Following an event, all categories of stakeholders (i.e., government, private sector interests, non governmental organizations, etc.) dispatch personnel to document the event's effects on the built environment. Data that are collected usually take the form of photographs and written descriptions of damage to facilities, where damage is expressed as subjective conclusions regarding buildings' systems as perceived by a particular stakeholder within a given constituency. The data are used to reconstruct the progress of damage to facilities. Based upon the reconstructions, an event's effects are often summarized in statements describing the damage to various classes of structures. Many examples of these qualitative studies can be found in the literature (e.g., CND 1983, 1984, 1991, 1994, FEMA 1993a, 1993b, HUD 1993, Marshall 1976, NOAA 1993, SEAOH 1983, 1993).

2.1.2. Forms developed by interested parties

Different groups have, at times, developed forms to collect data. The forms reflect what is

Table 3 Data collection method for each stakeholder

Stakeholder	Collection Method	Damage Measure
Independent	Independent user specific damage data	Subjective description
Insurance Industry	Insurance claims	Number of claims processed; Amount of paid claims
Local Governments	Building permit applications	Estimated construction costs, number of structures damaged
Various-1	Vulnerability algorithm data requirements	Nil (vulnerability estimation)
Various-2	Forms	Subjective description
Emergency Services	Independent data as-needed to support mission	Shelter population, days of lifeline and infrastructure disruption

perceived to be the critical items of interest to a particular group. For example, the American Association for Wind Engineering(AAWE) developed a form consisting of a two-page checklist that identified damage to the major features of a house. The damage survey form contains information about the surrounding terrain and exposure; the structure type and geometry; extent of damage to the roof, exterior walls, window systems, and exterior doors. Unfortunately, events have not produced sufficient damage to use extensively the form in the field since the form's creation in 1995. Advantages of this form are ease of use; its quick and easy check off system; and the ability to complete it in a timely manner. The predominant disadvantage is its lack of thoroughness in describing damage to a house.

2.1.3. Vulnerability estimation data requirements

Methods for estimating damage from natural hazards attempt to characterize the vulnerability of a structure for specified hazard levels. Previous studies have utilized a single hazard level in their algorithms; typically characterizing the vulnerability of a facility as its conformance to design criteria (e.g., building codes) (Culver *et al*, 1975, Hubenette and Reitherman 1985). Recently, automated vulnerability estimation has taken the form of commercial proprietary software. One example is WindRite (IBHS 1994), a software package that estimates the vulnerability of a building to wind events based upon the building's architectural and structural features, and the environment surrounding the structure as defined by ASCE-7/88 (ASCE 1990) (Mehta *et al.* 1991). Analysis of a structure results in an evaluation between 1.0 and 10.0 that represents the ability of the structure to resist a specified wind hazard. While the software was developed to estimate the vulnerability of a structure, validation of the methodology has been limited to collecting damage data according to the input requirements of the software. The extensive data required for analysis provides an exhaustive description of the property and surrounding environment; however, the large amount of time and effort spent in adverse conditions collecting data for a single facility limits the number of facilities that can be investigated after an event. Using the software as a tool to estimate vulnerability, the estimated state of damage to a facility is given as a number between 1.0 and 10.0 that reflects the relative potential for damage due to a given hazard.

2.1.4. Building permit data

After Hurricane Iniki (1992), Kauai County opened an Office of Emergency Permitting(OEP) to handle all applications for building permits. The OEP developed an electronic database as the primary source of documenting permit applications and tracking project progress. The database contains information that was obtained from non-electronic building permit applications. Although it was not intended in the original database design, much of the information gathered and stored electronically (such as type of damage, location of the structure, estimated cost of repairs and completion date) is beneficial to a formal damage quantification.

In addition to the information on the original building permit application, building inspectors were to have inspected houses after construction to ensure that work on the permit applications had been completed in compliance with the Kauai building code. An electronic damage data documentation system provides many benefits in that it facilitates systematic collection and easily accessible storage of electronic data, although the data do not contain fine detail. The data were often collected as checkmarks in boxes under "yes" or "no" headings, to indicate damage to structural and nonstructural elements such as plumbing, electrical and roof systems, and an estimate of repair costs was included for damaged components. A comment section in the report functioned as a record of whether the repair had been completed, and whether relevant permits had been obtained to complete the repair work. The report was extensive in the sense that it covered a wide range of components (OEP 1994) and recorded most of the damaged (complete devastation and minor damage) houses in the region.

2.1.5. Insurance claim forms

Insurance claim forms also provide documentation of damage. Claim forms from the insurance industry provide nominal descriptions of damage and an adjuster's estimate of the amount to be paid; however, access to the forms is often limited due to their proprietary nature, and the claims adjusters' descriptions of damage are extremely limited and of little value in analyzing damage statistics. Data from insurance claims exist for almost every significant event but can lead to mistaken impressions of damage because of the basis of an insurance claim. As described in Sparks and Bhinderwala (1993), drawbacks of using insurance claim forms include: only insured dwellings have damage documented; insurance claims are often paid at 100% when damage-in the adjuster's opinion-exceed 50% due to the terms of the policy; and the dollar value of the claim as reported by an insurance company includes items covered by a policy in addition to the value of the structure itself, which may be over- or under-insured. These additional costs include typically the value of personal property, temporary lodging, and debris removal. Since many insurance companies pay the total insured value rather than specifically for damaged areas, it is difficult to separate information related to property damage from the other losses.

2.2. Data collection for consistent damage quantification

In this research, the OEP database and the AAWE form were used as the basis for a data set and data collection methodology that would define a state of damage. These two sources satisfy the most significant constraints of the data collection procedure: documenting damage to a single house in a reasonable time, the limited number of personnel available for deployment, and providing quantitative and consistent data for calculating the damage index. Studies of the OEP database (Hossein, 1998) illustrate that it is the set of data most amenable to analyzing damaged houses statistically; while the OEP database has limitations in the amount of information that it contains, the digital storage medium is conducive to quantitative and spatial analysis. Features of a dwelling, in addition to those in the OEP database, that would be desirable to document by persons interested in collecting data in a timely manner were identified in the AAWE form. However, not all of the information in the AAWE form is easily stored electronically and, therefore, this research utilized a set of damage data based on both sources. Three systems are described by the set of data: External Architectural, Internal Architectural and Structural System. Based upon the data set that has been defined, a damage index was created that reflects the remaining functionality of a damaged dwelling. The systems and damage index are described in the following section.

3. Damage quantification

The first step in developing a consistent damage measure requires that a definition of damage be established. Ideally, the definition would describe the post-hurricane state of a dwelling using discrete, quantifiable measures. Furthermore, the definition should easily incorporate damage data collected immediately following a hurricane. In this research, the definition of damage is expressed as a damage index that reflects the state of damage to a single family detached dwelling on a fixed scale. Calculation of the index for a single dwelling uses the data collected via the formalized methodology described in the previous section.

Previous studies have provided typically qualitative descriptions of damage (Chiu 1993a, Chiu 1993b, Suaris and Khan, 1993). Few quantitative damage indicators have been proposed to describe structural damage due to extreme wind events. Sparks and Bhinderwala (1993) define damage as a ratio of the total insurance claim paid to the insured value of the structure and its contents. However, damage indices based on data from the insurance industry are misleading because data are available only for insured dwellings, there is limited resolution in the dollar losses for dwellings with between 50% and 100% damage, and the total insured value often is less than the insured value of the home. Based on the observation of over 600 houses after Hurricanes Andrew (1992) and Iniki (1992) Crandell *et al.* (1993) proposed a qualitative measure that ranks damage of the main components (roof, walls, foundation, and interior) into one of three qualitative categories (high, medium, and low) to evaluate the performance characteristics of different construction practices.

Following Cyclone Tracy (1974) data were collected on the structural damage to more than 2,200 dwellings. Preliminary analysis of the data immediately following the event provided information that was used in the emergency response and recovery efforts in the affected area. Subsequent analysis introduced damage classes that reflect the damage to structural members and systems (Leicester and Reardon 1976). Based upon the damage class, a damage index was assigned to a dwelling where the index is defined as the ratio of repair costs to initial costs. Damage that affects the functionality of a dwelling will often occur to nonstructural elements prior to the structural features being damaged. The damage index proposed in this research extends the work done by Leicester and Reardon by considering features of dwelling in addition to structural elements and systems. While the Leicester and Reardon index relate a form of economic loss (cost to repair damage) to the index, a dollar-damage relationship is beyond the scope of this paper and left to further research.

The usefulness of the damage descriptors proposed by Sparks and Bhinderwala (1993) and Crandell *et al.* (1993) are limited due to insufficient data and the lack of a consistent measure. A damage index is presented below to describe the state of damage for an individual dwelling. The index is defined relative to a fixed scale from zero to one with negligible damage to a dwelling denoted by zero, and complete devastation denoted by one. The index is dependent on collecting the recommended field data discussed in the previous section. The objective of the index is to capture succinctly and quantitatively the essence of a damaged house using consistent measures based on observed damage, and to relate component-level damage to system-level structural integrity.

The damage index, I_D, for a building system is shown in Eq. (1) and is a function of the damage to three main systems, the weight factor for each system, and the correlation between the damage of two systems.

$$I_D = \frac{\sum_{i=1}^{3} S_i \left(W_i + \sum_{j=1}^{3} C_{ij} \right)}{100 \sum_{i=1}^{3} \left(W_i + \sum_{j=1}^{3} C_{ij} \right)} \qquad (1)$$

where S_i is the damage index for system i, W_i is the associated weight factor, and C_{ij} is a correlation weight factor that incorporates the interaction between the damage of systems i and j into the total damage quantified for the dwelling.

The system indices (presented in Table 4) for the external architectural (EA) system, internal architectural (IA) system, and the structural system (SS) quantify the magnitude of damage, and the weight factors represent the influence of each system on the overall functional integrity of a damaged dwelling. Damage to a building's contents does not compromise the functionality of the structure and is not included within the definition of non-structural damage and, therefore, is not included in the damage index presented in this paper.

Non-structural systems are divided into two categories: EA and IA systems. Loss of external components, although not required for structural stability, may compromise the building envelope and result in a discontinuous external seal leading to successive failures of the overall integrity of the structural system. Internal components are defined as components that are essential to the function of the dwelling (e.g., interior partitions, mechanical, electrical and plumbing systems) but do not provide a seal nor are essential to the overall structural stability of the dwelling. The SS and its components are the most significant to structural integrity and are essential to the overall stability of the dwelling and the integrity of the EA components that complete the building envelope (doors, windows, and garage doors). Components that comprise SS are the gable-end walls, roof trusses, and structural walls.

Initial weights are assigned to the major components based on their importance to the overall integrity of the dwelling. Damaged EA components do not compromise the overall structural integrity of the house; however, they are significant as the loss of protection can reduce the functionality of a dwelling and induce further structural damage. The weight associated with EA

Table 4 System damage definitions

i	System	Definition	Components
1	External Architectural (EA)	Components on the exterior of the structure that must be damaged before the structural system is damaged.	Roofing, siding, windows, doors, large openings, garage door (if garage is attached)
2	Internal Architectural (IA)	Components that are nonessential to the stability of the dwelling but are essential amenities.	Sheetrock & gypboard walls, ceiling, mechanical, electrical, and plumbing systems
3	Structural System (SS)	The structural components essential to the stability of the structure and the integrity of the EA components that complete the building envelope.	Roof, roof truss system, structural walls (interior and exterior), end walls (gable and hip), roof/wall connections

is 0.3, $W_{(i=1)} = 0.3$. Failure of IA components can significantly hinder the functionality of the dwelling. Although IA damage is not likely to contribute to successive structural damage, significant IA damage can not occur unless the structure has experienced EA damage. The weight factor for IA is 0.3, $W_{(i=2)} = 0.3$. The structural system (SS) is the most important with regard to the building's stability and is assigned the highest weight factor, $W_{(i=3)} = 0.4$.

S_i is the percent damage for each of the three main systems. In general, percent damage is calculated based on the quantity of damaged components or sub-components. For example, the percent damage of the sub-component, such as a truss system, is equal to the ratio of the number of failed sub-components to the number of original sub-components. Percent damage for sheathing and outside walls is the ratio of the damaged area to the total area. Construction quality, especially with regard to fasteners, has been raised as a concern after major hurricanes. Hossein (1998) suggests percent damage for S_i values for the gable-end walls that are based on the qualitative descriptions given in Table 5.

The effect a damaged system has on overall structural integrity is dependent on the severity of damage. The weight factors (W_i) incorporate the weight or importance of the damage to a system to the overall integrity of the structure. A structure is inherently more susceptible to damage as the system damage indices (S_{EA}, S_{IA}, and S_{SS}) increase and the damage to one system can influence damage to the others. Thus, the damage index for a structure is nonlinear and is dependent on the damage to the individual systems and the interaction between the systems. The correlation between damage states is incorporated into a correlation matrix that increases the weight of each system based on the severity of damage to the other systems. The correlation between damage states less than and greater than 50% are given in Eqs. (2) and (3), respectively.

$$C_{S<50} = \begin{array}{cc} \begin{bmatrix} 0 & 0.2 & 0.2 \\ 0.2 & 0 & 0.8 \\ 0.2 & 0.9 & 0 \end{bmatrix} & \begin{array}{c} EA \\ IA \\ SS \end{array} \\ \begin{array}{ccc} EA & IA & SS \end{array} & \end{array} \tag{2}$$

$$C_{S\geq 50} = \begin{array}{cc} \begin{bmatrix} 0 & 0.1 & 0.1 \\ 0.8 & 0 & 0.1 \\ 0.8 & 0.1 & 0 \end{bmatrix} & \begin{array}{c} EA \\ IA \\ SS \end{array} \\ \begin{array}{ccc} EA & IA & SS \end{array} & \end{array} \tag{3}$$

Table 5 Gable-end damage index (after Hossein 1998)

Qualitative Description of Damage	% Damage
Superficial cracks in masonry walls	0%
Non-superficial cracks in masonry gable end walls that can be repaired by structural methods	20%
Non-superficial cracks in masonry gable end walls that cannot be repaired by structural methods	75%
Wood-frame gable end walls that have been dislocated or have fallen over	100%

Eq. (2) is used to obtain the correlation ($C_{s<50\%}$ (i, j)) between systems i and j if the damage for component i is less than 50%. Whereas, if the damage for system i is greater or equal to 50%, Eq. (3) is used to obtain the correlation factors between systems i and j. The interaction between components is not commutative and symmetry is not a requirement for the correlation matrices. The correlation factors increase the weight assigned to each of the three systems considered in Eq. (1). The coefficients that appear in Eqs. (2) and (3) are obtained considering the influence between the damage to one system component on another system component. There are a number of physical requirements for the damage index presented in to following section.

3.1. Physical requirements for the damage index

There are a number of failure mechanisms that a structure can experience due to hurricane induced damage. Typically, for any failure mechanism, the damage to EA components is greater than damage to IA and SS components. The building's envelope must be broached before the internal components of a dwelling are affected, thus EA component damage must be greater than IA component damage. It is difficult for SS components to fail without EA and IA components suffering failures in the same regions. Therefore, EA and IA damage must be at least equal to SS damage and the following requirement is asserted for the system damage levels:

$$S_{EA} \geq S_{IA} \geq S_{SS} \tag{4}$$

Increased damage to any S_i must result in an increased I_D. Therefore, the damage index must increase monotonically with respect to the damage of each system. I_D must also increase at regions of discontinuity. Written mathematically, the physical requirements for I_D are :

1. The damage index increases monotonically with respect to damage of each system.

$$\frac{\partial I_D}{\partial S_i} \geq 0 \text{ for all } i \tag{5}$$

2. The damage index increases at a higher rate once a system suffers at least 50% damage.

$$\left.\frac{\partial I_D}{\partial S_i}\right|_{S_{j,k} \geq 50} \geq \left.\frac{\partial I_D}{\partial S_i}\right|_{S_{j,k} < 50} \text{ for } i \neq j \neq k \tag{6}$$

where $S_{j,k}$ denotes the partial derivative with respect to variable S_j or S_k.

3. The damage index must increase with increasing system damage at the regions of discontinuity.

$$I_D \,|_{S_j \geq 50} - I_D \,|_{S_j < 50} \geq 0 \tag{7}$$

for each j when damage for the other systems is constant.

4. The damage index must increase with increasing values for S_{EA} at the initial condition states for the SS and IA systems. ($S_{IA} = S_{SS} = 0$)

$$I_D \, (S_{IA} = S_{SS} = 0) \,|_{S_{EA} \geq 50} \geq I_D \, (S_{IA} = S_{SS} = 0) \,|_{S_{EA} < 50} \tag{8}$$

The physical requirements impose conditions on the values of the weight factors and correlation factors. Requirement 1 will hold if

$$\left(w_i + \sum_{j=1}^{3} C_{ij} \right) \geq 0 \text{ for each } i \tag{9}$$

Requirement 2 will hold if

$$\left(\left. \frac{\left(w_i + \sum_{j=1}^{3} C_{ij} \right)}{\sum_{i=1}^{3} \left(W_i + \sum_{j=1}^{3} C_{ij} \right)} \right|_{\geq 50\%} \geq \left. \frac{\left(w_i + \sum_{j=1}^{3} C_{ij} \right)}{\sum_{i=1}^{3} \left(W_i + \sum_{j=1}^{3} C_{ij} \right)} \right|_{< 50\%} \right) \text{ for each } i \tag{10}$$

when $S_j \geq 50\%$ and $S_k \geq 50\%$.

Requirement 3 will hold if Eq. (9) is true and

$$S_i\,(d+1) \geq S_i\,(d) \tag{11}$$

where d is the percent damage for system i.

Requirement 4 will hold if

$$\frac{\left[W_1 + \sum_{j=1}^{3} C_{1j} \right]_{S_{EA} \geq 50\%}}{\left[W_1 + \sum_{j=1}^{3} C_{1j} \right]_{S_{EA} \geq 50\%} + \left[\sum_{i=2}^{3} \left(W_i + \sum_{j=1}^{3} C_{ij} \right) \right]_{S_{IA}, S_{SS} < 50\%}} \geq \left. \frac{W_1 + \sum_{j=1}^{3} C_{1j}}{\sum_{i=1}^{3} \left(W_i + \sum_{j=1}^{3} C_{ij} \right)} \right|_{S_{EA} < 50\%} \tag{12}$$

It should be noted that Table 4 defines systems 1, 2, 3 as EA, IA, and SS, respectively. Surface plots of the damage index in terms of the three major components are shown in Fig. 1 for constant S_{ss} values. Damage index values within the domain ($S_{EA} \geq S_{IA} \geq S_{SS}$) are described by the mesh surface. The regions of the mesh surface that imply zero damage index values fall outside the domain and are invalid. Since it is difficult to read values from the mesh surface, Figs. 2a and 2b show planes cut through the I_D surface at $S_{IA} = S_{SS}$ and $S_{IA} = S_{EA}$. The dashed line represents the boundary between the valid and invalid domains defined by Eq. (4).

3.2. Damage index validation

The damage index and its governing parameters are designed to be adaptive with additional calibrations performed after each damaging event. Initial steps in a verification process include comparing the value of the damage index and the information about the damaged structure to ensure that the damage index reflects actual state of damage.

The functionality (F) of a dwelling after a damaging event is related to the damage incurred and is defined as :

$$F = 1 - I_D \tag{13}$$

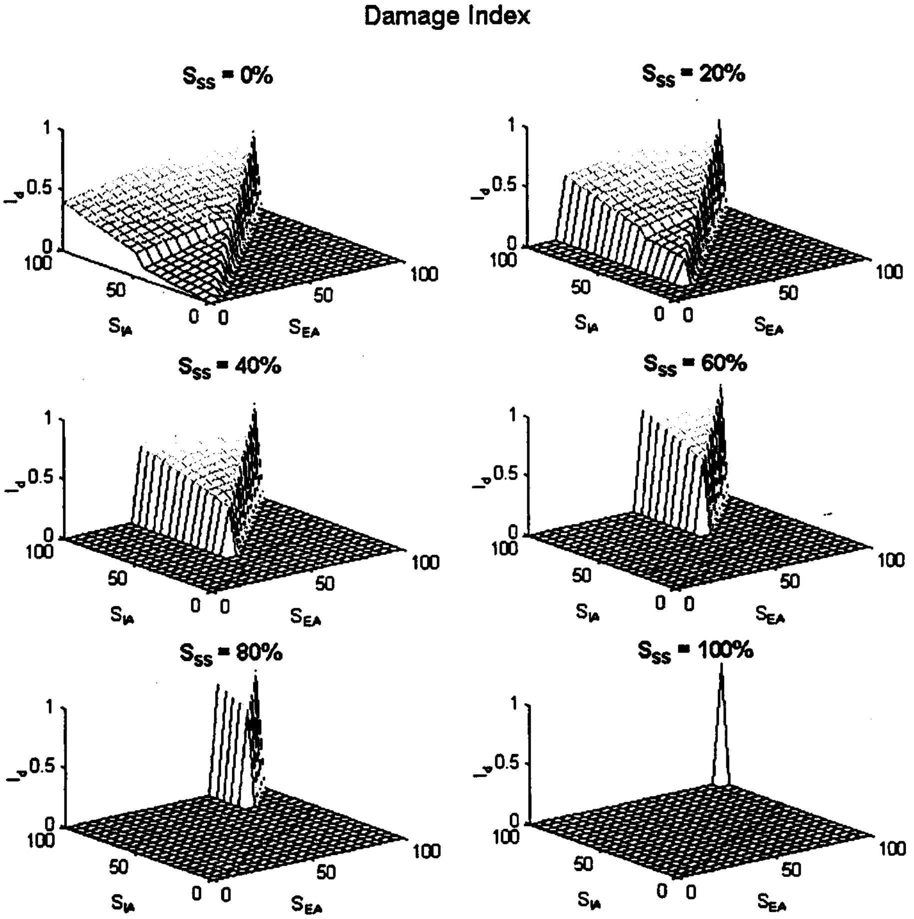
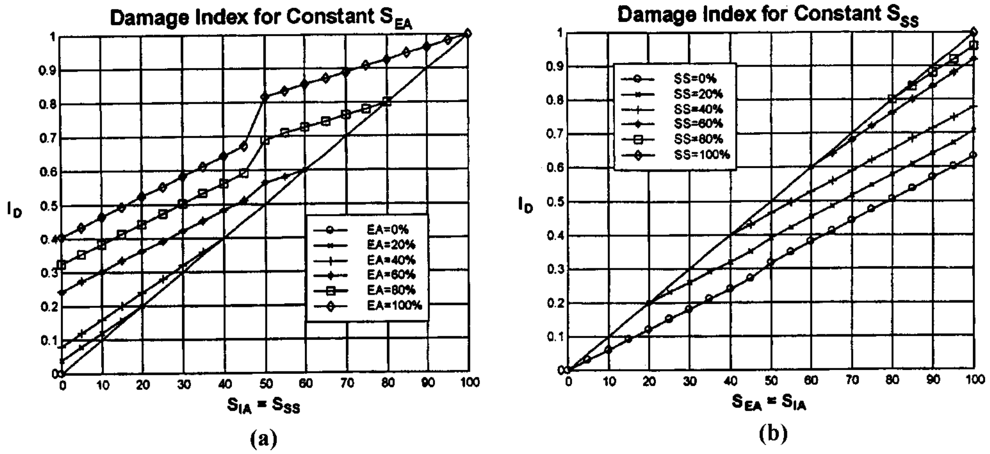


Fig. 1 Sensitivity analysis of I_D for the three system damage indicators



(a) (b)

Fig. 2 Sensitivity analysis of I_D for $S_{IA} = S_{SS}$ (a) and $S_{EA} = S_{IA}$ (b)

The index approaches 1.0 slowly for high percentages of EA, IA, and SS damage due to the normalization of the damage index to a maximum value of 1.0. Typically, dwellings that are severely damaged will have damage index values greater than 0.75. The index provides significant resolution for structures that experience moderate damage and varies from about 0.25 to 0.75. Structures experiencing only minor damage will have I_D values less than 0.25. Due to the normalization enforced on I_D the functionality is not a representation of percent usefulness remaining in the dwelling. However, general relationships between functionality levels and usefulness can be asserted. Functionality levels between 0.85 and 1.0 imply that the dwelling is still inhabitable during repair while dwellings with functionality between 0.5 and 0.8 are not inhabitable. Further resolution can be defined after the damage index and correlation factors are calibrated with field data.

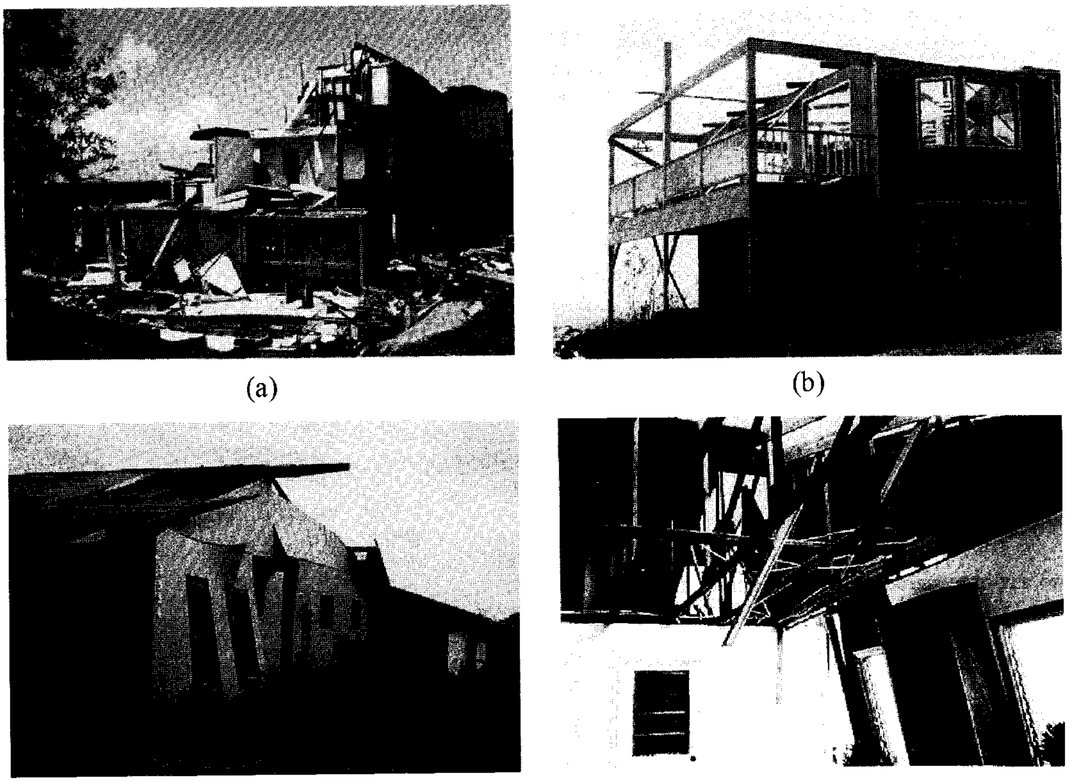
A complete calibration of the damage index should consider the event magnitude, the surrounding terrain, and the extent of structural damage for different structure types. The damage index calibration consists of two significant steps. The first is the selection of W_i and C_{ij} factors that meet the physical requirements for I_D as discussed in the previous section and represent the building type considered. Further refinement of W_i and C_{ij} require an iterative process that validates documented damage and functionality to the quantified I_D. The second is the evaluation of I_D and verification of the result with regard to visual inspections. Due to the lack of data that have been documented consistently, electronically, or in a quantifiable manner with regard to building systems, a formal calibration of the damage index is not presented here. For the purposes of this paper the visual inspections are simulated through the use of photographs that document damage to single family houses after Hurricane Iniki (1992). The following section presents an example of the damage index application.

4. Case study

Hurricane Iniki devastated the island of Kauai on September 11, 1992 causing more than 90% of the structures on the island of Kauai to sustain some level of damage. The estimated maximum sustained wind velocity for the Category 4 (Saffir-Simpson scale) hurricane was 52. 4±2 m/s with peak gusts as high as 63 m/s. The hurricane passed over the center of the island in less than 45 minutes with an eye 18.5 km in diameter (Chiu *et al.* 1995). The Damage Index is evaluated for three dwellings (shown in Fig. 3) at different locations on the island that suffered severe and moderate damage.

4.1. Structure 1: Severe damage

Fig. 3a shows a severely damaged single family residence located in Princeville, which lies on the north shore of Kauai, and was in the path of the hurricane. Most of the EA system components (external sheathing and compoments that envelope the structure) have been torn from the structure, exposing the IA system and SS. Thus, the IA system suffered significant damage and few structural components remain standing. The estimated system damage to EA, IA, and SS are 90%, 80%, and 80%, respectively.



(a) (b)

(c) (d)

Fig. 3 Case study dwellings: (a) Severe damage to a structure located in Princeville. (b) Moderate damage to a structure with a verandah. (c & d) Exterior and interior view of a structure in Lihue

4.2. Structure 2: Moderate damage

The structure shown in Fig. 3b had a verandah roof that is extremely vulnerable to extreme winds. The verandah was torn off the structure causing failure to the roof framing. Here the primary EA failure is damage to the verandah and roof sheathing. The IA system failures consist of interior wall failure, ceiling loss, and loss of systems (electrical and plumbing). The primary structural damage is the complete loss of the roof system. The estimated system damage to EA, IA, and SS are 75%, 60%, and 40%, respectively.

4.3. Structure 3: Moderate damage

External and internal views of the moderately damaged dwelling located in Lihue are shown in Figs. 3c and 3d. Lihue is on the coast and about 20 km to the west of the storm's path. Gable roof end-wall failure was the primary failure mechanism. The primary EA failures are the sheathing from the roof, cladding failure and the opening of the building envelope. The IA system failures consist of ceiling and interior wall failure. The primary damage to the structural component was the gable end wall failure. The estimated system damage to EA, IA,

Table 6 Damage index computation for three case study structures

Component	Structure 1			Structure 2			Structure 3		
	S_I	W_I	$\sum_{j=1:3} C_{ij}$	S_i	W_I	$\sum_{j=1:3} C_{ij}$	S_i	W_i	$\sum_{j=1:3} C_{ij}$
EA ($i = 1$)	90	0.3	1.6	75	0.3	1.6	50	0.3	1.6
IA ($i = 2$)	80	0.3	0.2	60	0.3	0.2	40	0.3	0.2
SS ($i = 3$)	80	0.4	0.2	40	0.4	1.0	30	0.4	1.0
		$I_D \rightarrow$	0.86		$I_D \rightarrow$	0.60		$I_D \rightarrow$	0.41

and SS are 50%, 40%, and 30%, respectively.

Computations of the damage indices for the three structures shown in Fig. 3 demonstrate the potential variability in I_D. Table 6 lists a summary of the system damage for the three case-study structures. The resulting values of 0.86, 0.60, and 0.41 denote the overall damage to the structures. The remaining functionality ($F = 1 - I_D$) is evaluated as 0.14, 0.40, and 0.59 for the three structures, respectively.

As discussed previously, the index approaches 1.0 slowly for high percentages of EA, IA, and SS damage due to the normalization of the damage index to a maximum value of 1.0. Dwellings that are severely damaged will have damage index values greater than 0.75. The index provides significant resolution for structures that experiences moderate damage and varies from about 0.25 to 0.75. Structures experiencing only minor damage will have I_D values less than 0.25.

5. Conclusions

Significant monetary losses and devastating structural damage due to severe wind events have motivated the need for consistent data collection and evaluation. While different rational methods to collect data related to structural damage have been proposed and developed, only singular efforts have been made to utilize these methods. Thus, documentation and quantification of damage for the purpose of analyzing the amount of damage occurring to the population of houses in an affected area has not been possible previously. The impetus for this research is the need to define hurricane induced damage to single family dwellings, document damage that results from hurricanes in a systematic manner and provide a framework that will allow damage to be compared among a population of houses or series of events. A method is introduced that addresses these issues and applied to some houses that were damaged in Hurricane Iniki. While a hazard-damage relationship would relate a damage level to a measure of economic loss, the research presented addresses only those topics addressed above. The proposed approach integrates quantitative data currently collected in the AAWE form, geographic and cost data collected in the OEP database with digital photographs and percent damage to EA, IA, and SS into an electronic storage median.

A damage index is defined that measures the functionality of a dwelling after a hurricane. The index quantifies the damage state due to the three primary structural systems: EA, IA, and SS where the percent damage to each system is documented using a simple data collection methodology. The fixed-scale makes it possible to compare damage among different dwellings and events. Finally, the index is applied to three structures damaged by Hurricane Iniki.

This research has illustrated a damage index that quantifies the relative damage to a structure with the data for the analysis being obtained through visual observation. The data for the index have been limited to a few selected items that reflect the systems of the house and that would be easily amenable to collection in the field using forms either written or electronically. Implementation of the proposed data collection methodology and damage evaluation using the new index for a population of dwelling will yield valuable information about the amount of damaged suffered or the amount of functionality remaining in a region.

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