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The development of wind damage bands for buildings

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Abstract

The past decade in the United States was marked by a tremendous loss in properties attributed to wind damage, generating in the process, an enormous awareness to the twin problems of wind damage mitigation and storm prediction. This paper proposes a new approach to hurricane wind damage prediction using the concept of wind damage bands. The damage band prediction methodology employs an objective weighting technique driven by building component cost factors, component fragilities, and location parameters to obtain upper and lower bounds to building damage thresholds. Damage bands are developed for 1–3 story (low-rise) buildings as well as 4–10 story (mid-rise) buildings. The damage bands reveal that the wind damage response of individual 1–3 story buildings is most easily distinguished in the 43–60 m/s (sustained one-min mean) wind regime and that above 73 m/s sustained one-minute wind speed, 1–3 story buildings experience near-total destruction of their superstructures, with the damage response of the most wind-resistant and least wind-resistant building approaching each other. In contrast, the damage response of individual mid-rise buildings is most easily distinguished in the 60–81 m/s wind regime, and continues to depend largely upon the components and connections. Wind damage bands form the basis for new methods of wind damage prediction of individual buildings and groups of buildings, wind damage mitigation, and emergency management planning. © 2000 Elsevier Science Ltd. All rights reserved.

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Nomenclature

a_{i1}, a_{i2}	wind speeds at which damage will commence and be total in the ith damage mode
BSE	building specific evaluation modifier
c	minimum life in Weibull distribution
CCF_i	component cost factor
COM(U), COM(L)	upper and lower damage functions, respectively for 1–3 story commercial buildings
$\boldsymbol{D}$	damage matrix
$\mathrm{DD}(l)$	damage degree (or percent damage) at hazard level l
DPM	damage probability matrix
$\mathrm{DR_c}(v)$	building contents damage ratio
DR_i	damage ratio for the ith damage mode
$\mathrm{DR}_i^{\mathrm{c}}$	content damage given damage of component i of the structure
DR_k	damage ratio for content type k
$\mathrm{DR_s}(v)$	building damage ratio
E	event
ED&W	exterior doors and windows
ED&W/EW	exterior doors and windows damage given damage of exterior wall
ED&W/RS	exterior doors and windows damage given damage of roof structure
EW	exterior wall
EW/ED&W	exterior wall damage given damage of exterior doors and windows
EW/RS	exterior wall damage given damage of roof structure
$f_L(l)$, $f_R(r)$	marginal probability density functions of L and R, respectively
F-OR	function "OR" (special user-defined OR gate)
$F_R(l_i)$	cumulative distribution function of the resistance variable R
GAE	general analytical evaluation modifier
GEE	general empirical evaluation of a building
HVE	hurricane vulnerability evaluation
I_i	relative importance of the ith damage mode
INST(U), INST(L)	upper and lower damage functions, respectively, for 1–3 story institutional buildings
INT	interior
J_i	relative importance of the ith damage mode to the damage ratio of the contents
l_i	ith load effect
$\boldsymbol{L}$	loss vector, mean damage ratio matrix, load variable, model specification matrix
LN(*,*)	lognormal distribution
m_R	median of the resistance variable R

n	number of components, number of experts
$N(*,*)$	normal distribution
O_i	ith expert's estimate
$\boldsymbol{P}$	windstorm strike probability vector, hazard state probability matrix
$P(E_1)$,$P(E_2)$	individual probabilities of failure of events E_1 and E_2, respectively
$P(E_1E_2)$	joint probability of failure of any two events E_1 and E_2
P_f	conditional probability of failure
P_{f_i}	component conditional probability of failure (or component fragility)
$P^\mathrm{B}_{\mathrm{f}_i}$	component basic fragility
$P^\mathrm{P}_{\mathrm{f}_i}$	component conditional probability of failure due to propagational effects
P_i	aggregated response of experts for the ith question
$P(\mathrm{INT}/C_i)$	probability of interior damage given that the ith component is damaged
P(interior damage)	conditional probability of damage of the building interior
R	resistance variable, expert's rating
RC	roof covering
RC/RS	roof covering damage given damage of roof structure
RCF_i	relative component cost factor
RES(U), RES(L)	upper and lower damage functions, respectively, for 1–3 story residential buildings
RS	roof structure
RS/ED&W	roof structure damage given damage of exterior doors and windows
RS/EW	roof structure damage given damage of exterior wall
S	unbiased estimator for standard deviation
Sh1, Sh2, Sh3, Sh4	fault tree diagrams denoted by sheet numbers 1, 2, 3 and 4, respectively
TEM	terrain evaluation modifier
v	wind speed
V	sustained 1-min surface wind speed
$W(*,*)$, $W(*,*,*)$	2- and 3-parameter Weibull distribution, respectively
α_i	component location parameter (or component damage localization factor)
β	scale parameter in Weibull distribution
μ_R	mean of the resistance random variable R
$\rho_{1,2}$	correlation coefficient between failure of two components 1 and 2
$\sigma_{\ln(R)}$	logarithmic standard deviation of the resistance variable R
σ_R	standard deviation of the resistance random variable R
$\Phi(\cdot)$	cumulative distribution function

Subscripts

α	shape parameter in Weibull distribution, level of significance
i,k	indices for components, experts, variables
∞	infinity

1. Introduction

The dramatic increase in the value of properties lost in hurricanes during the past decade has resulted in an increased awareness of the enormity of the hurricane wind damage problem, earning it the unenviable position of number one catastrophe in terms of dollar loss in the United States. Unfortunately, the important issues of wind damage prediction and mitigation have not kept pace with this level of recognition of the wind hazard. Wind damage prediction is an issue because all existing structures are not windstorm-resistant. When this fact is combined with recent climatic changes favorable to major hurricane occurrences on the US east coast [1], and the fact that most structures located in the hurricane-prone coastal areas are insured against wind damage, the need for an adequate tool for predicting and mitigating wind damage becomes all the more compelling.

In general, two types of damage prediction methods may be distinguished, namely, qualitative and quantitative methods. Qualitative damage predictions describe the likely damage levels associated with different building categories and/or hurricane wind intensities. Typical examples of qualitative damage predictions are: (1) the classification of buildings as either fully engineered, pre-engineered, marginally engineered, or non-engineered, with their associated wind damage performances [2], and (2) the Saffir/Simpson damage potential scale [3,4]. Qualitative approaches to wind damage prediction serve general purposes only and do not predict damage to specific buildings. Quantitative approaches which consider structure characteristics are essential for the reliable prediction of damage to buildings.

A review of the technical literature on quantitative wind damage prediction indicates a great deal of reliance on expert input. This is largely attributable to the lack of test data on the behavior of materials under extreme wind loading and the heuristic nature of the wind damage phenomenon. A method for regional estimation of tornado damage for general structural types was proposed by Hart [5]. Using expert-supplied damage matrices, Ref. [5] presented wind speed/damage relationships for 1–3 story wood-framed and masonry/concrete wall residential structures, 1–3 story metal industrial structures, structures greater than 4 stories, mobile homes, and windows. Hart [5] evaluated the expected annual dollar loss for each damage state under 1970 conditions, according to the equation

$$\text{Total wind damage} = \{\boldsymbol{L}\}^{\mathrm{T}}[\boldsymbol{D}]\,\{\boldsymbol{P}\}. \tag{1}$$

In the above equation, $\{\boldsymbol{L}\}$ is a loss vector, $[\boldsymbol{D}]$ the damage matrix, and $\{\boldsymbol{P}\}$ the windstorm strike probability vector. Although not suitable for damage prediction of specific buildings, this pioneering work holds promise for evaluating the expected annual loss of buildings within a specified geographic region.

Building wind vulnerability relationships have also been obtained by analyzing weather data and insurance claim files [6,7]. Ref. [7] analyzed approximately 250 claim files of one insurer and plotted overall loss ratio and direct damage ratio for groups of reinforced masonry-wall single family dwellings against gradient wind speeds obtained from airforce reconnaissance aircraft measurements [8] shortly before the landfall of Hurricane Andrew. The overall loss ratio was defined as the total claim paid (including the amount paid for additional living expenses and debris removal) divided by the insured value of the structure and its contents, while the direct wind damage was considered to be the cost of repairs to the roof, doors, windows, walls, and the external facilities. Ref. [7] concluded that a very sudden increase in the overall loss ratio occurs when the gradient wind speed exceeds 70 m/s due to the breakage of windows and damage to roofs. While the sole use of such wind speed/damage relationships derived from past damage data and traditional actuarial procedures may not provide a consistent measure of present or future risk [6], they reveal information useful in validating wind speed–damage prediction models.

In a pioneering work to simulate building contents damage in hurricanes, Stubbs and Boissonnade [9] proposed a model using roofing failure and openings as the hazards which affect content damage, and the damage probability concept. The damage ratio for content type k, DR_k, was given as

$$\mathrm{DR}_k = \boldsymbol{L}[\mathrm{DPM}]\boldsymbol{P}, \tag{2}$$

where $\boldsymbol{L}$ is a 1×6 matrix containing the mean damage ratios, DPM a 6×6 damage probability matrix, and $\boldsymbol{P}$ a 6×1 matrix containing the probability that the building envelope is in one of six final hazard states. However, a more comprehensive methodology was subsequently proposed by Stubbs et al. [10], in which the building contents damage ratio, $\mathrm{DR_c}(v)$, was given by

$$\mathrm{DR_c}(v) = \frac{\sum J_i\, \mathrm{DR}_i^{\mathrm{c}}\, \mathrm{DR}_i}{\sum J_i}. \tag{3}$$

In Eq. (3), J_i is the relative importance of the ith damage mode to the damage ratio of the contents, $\mathrm{DR}_i^{\mathrm{c}}$ the content damage given the damage of component i of the structure, and DR_i the damage ratio for the ith damage mode (see Eq. (5)). Also proposed in Ref. [10] is a model for building damage ratio, $\mathrm{DR_s}(v)$, in terms of expert-supplied wind speed/building damage mode parameters according to the following equation:

$$\mathrm{DR_s}(v) = \frac{\sum_{i=1}^{9} I_i\, \mathrm{DR}_i(v)}{\sum_{i=1}^{9} I_i} \tag{4}$$

where I_i is the relative importance of the ith damage mode to the damage ratio of the entire structure, subscript 9 the number of components, and

$$\mathrm{DR}_i(v) = \begin{cases} 0, & v \leqslant a_{i1} \\ \dfrac{v - a_{i1}}{a_{i2} - a_{i1}}, & a_{i1} < v \leqslant a_{i2}, \\ 1, & v > a_{i2}, \end{cases} \tag{5}$$

is the damage ratio for the ith damage mode, v the wind speed, and a_{i1} and a_{i2} are respectively, the windspeeds at which damage will commence and be total in the ith damage mode. The usefulness of this procedure for damage evaluation of broad building classes is heavily dependent upon the availability of reliable values of the constants a_{i1} and a_{i2}.

A hurricane vulnerability model for single-family dwellings was proposed by Chiu [11], in which expert-supplied damage probability matrices were employed as the general empirical evaluation of a building (GEE). The GEE was then modified by a general analytical evaluation (GAE), a terrain evaluation (TEM), and a building-specific evaluation (BSE), to obtain the hurricane vulnerability evaluation (HVE), as follows:

$$\mathrm{HVE} = \mathrm{TEM}\,(\mathrm{GEE} - \mathrm{GAE} + \mathrm{BSE}). \tag{6}$$

The model [11] may be applied to predict damage to a specific single-family home. It is, however, considered coarse, as the general analytical evaluation does not adequately account for the major failure modes of a building, including damage due to windborne debris.

In the present work, we propose a new concept that utilizes building damage bands for addressing the wind damage prediction problem. This paper presents the results of a recently concluded study at Texas Tech University's Wind Engineering Research Center. The emphasis in this paper is on the procedure for developing wind damage bands for buildings. A building wind damage band defines the upper and lower thresholds of damage degree–wind speed relationships for buildings in an occupancy class or for particular types of buildings within an occupancy class. In addition to their use in determining general characteristics of building failure in extreme winds, building wind damage bands may be employed with specific building wind performance information to predict damage to individual buildings or groups of buildings, and for wind damage mitigation.

2. Proposed model

The proposed model for determining the degree of damage to any given building or group of buildings is based upon the "damage band" for the building type(s) or class(es) of interest. We define a wind damage band as the damage degree range bounded by a lower and upper damage threshold for given intensities of the wind hazard. The upper and lower damage thresholds are determined, respectively, for the set of building components and connection characteristics that are associated with the highest and lowest probabilities of failure in a windstorm, using the following equation:

$$\mathrm{DD}(l) = \sum_{i=1}^{n} P_{\mathrm{f}i}(\mathrm{CCF}_i)\alpha_i \tag{7}$$

In the above equation, DD(l) is the damage degree (or percent damage) at hazard level l, $P_{\mathrm{f}i}$ the component conditional probability of failure (or component fragility), CCF_i the component cost factor, α_i the component location parameter (or component damage localization factor), and n the number of components used in the building damage model. The terms in Eq. (7) are explained in the sections that follow. Implicit in Eq. (7) is that a building suffers some degree of damage if there exists a probability of failure of at least one of its components. In this case, damage to a building component could result from damage to the connection of that component to other components, or from damage in the domain of the component. Based on the relative likelihood of damage and cost contribution of a building component, the present model considers a building as composed of the following components: roof covering, roof structure, exterior doors and windows, exterior wall (includes finishes, electrical and mechanical components supported, cladding and support systems), interior (including contents), structural system (includes columns, girders, elevated floors, and conveying equipment), and foundation.

An overall picture of the damage process used in the model is shown in the schematic diagram of Fig. 1. Fig. 1 shows that each building component may suffer

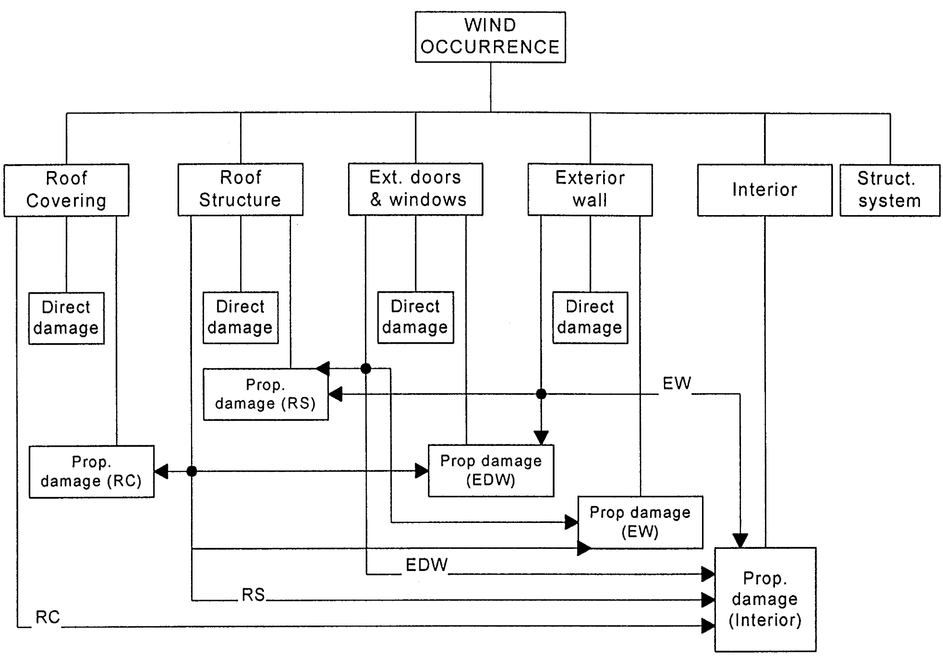

Fig. 1. Wind damage process.

damage either through the direct impact of the wind or as a result of damage of other components (i.e., damage propagation). Each building component (except the structural system and interior) in the damage model is connected with three lines. The first line indicates its contribution to the propagational damage of other components, while the second and third lines show the component's direct (basic) damage and propagational damage, respectively. Since the basic and propagational damage of a building component in a windstorm are not necessarily mutually exclusive, the final component damage response to varying levels of the wind hazard, in terms of probability of failure, $P_{\mathrm{f}i}(l)$, is obtained by combining the two effects as follows:

$$P_{\mathrm{f}i}(l) = P^{\mathrm{B}}_{\mathrm{f}i} + P^{\mathrm{P}}_{\mathrm{f}i} - P^{\mathrm{B}}_{\mathrm{f}i}P^{\mathrm{P}}_{\mathrm{f}i} \tag{8}$$

where $P^{\mathrm{B}}_{\mathrm{f}i}$ is the component basic fragility, i.e., component conditional probability of failure due to wind pressures and windborne missiles, and $P^{\mathrm{P}}_{\mathrm{f}i}$ the component conditional probability of failure due to propagational effects.

3. Component fragilities

The building component fragilities are obtained by analyzing a multiple fault tree scheme in which the damage of the components serve as the top events. The fault tree diagrams for the explicitly modeled building component damage modes are shown in Figs. 2–10. Component basic fragilities are given by the probabilities of the intermediate events labeled B1–B4 in the fault trees while component propagational failures are indicated by the intermediate events whose labels begin with the letter P. For practical reasons, the failure modes modeled in the fault trees are those that are predominant in hurricanes and can also contribute significantly to overall building damage. We assume that building foundations are not subject to damage. Although the structural systems of buildings should be considered in determining individual building damage resistivities, their damage probabilities are orders of magnitude less than those of roof covering, roof structure, exterior doors and windows, and exterior wall, and are therefore not explicitly modeled in the fault trees. However, conservative allowances have been made in developing the damage bands to account for their damage susceptibilities in low-rise buildings. For purposes of clarity, we have used repeated events in the fault trees. These are, however, removed during the fault tree analysis using Boolean algebra relations [12].

The probability of failure of the basic events (i.e., lowest level events represented by circles in the fault trees) are obtained by considering the wind pressure and the strength of components and connections as the load (L) and resistance (R) variables, respectively, using the stress–strength interference method [13]. From the classical time-invariant probability of failure expression for random-fixed stress and random-fixed strength (Eq. (9)), the conditional probability of failure for deterministic loads and random-fixed strength variables is given by Eq. (10):

$$P_{\mathrm{f}} = \int_{-\infty}^{\infty} f_L(l)\left[\int_{-\infty}^{l} f_R(r)\,\mathrm{d}r\right]\mathrm{d}l \tag{9}$$

$$P_f(l_i) = P(R \leqslant l_i) = \int_{-\infty}^{l_i} f_R(r)\,\mathrm{d}r = F_R(l_i) \tag{10}$$

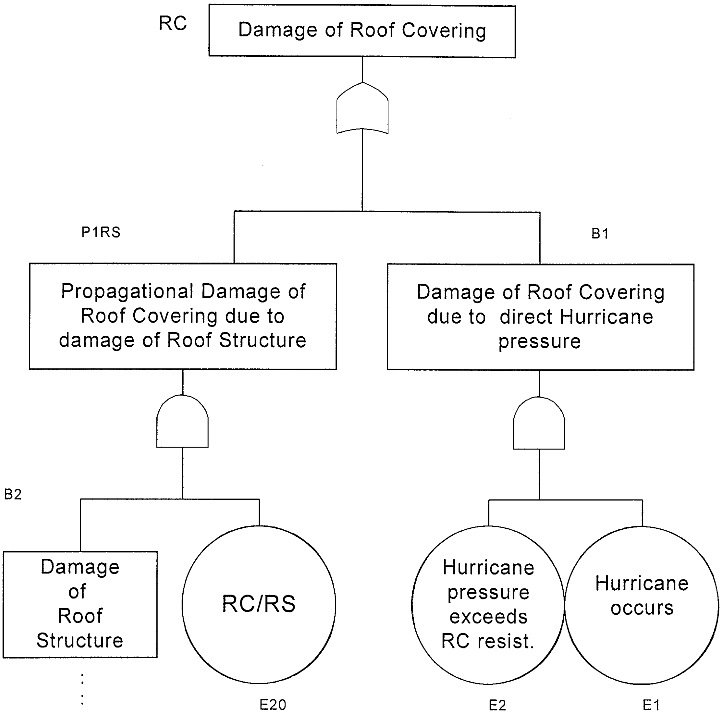

Fig. 2. Fault tree for roof covering damage.

In (9) and (10), $f_R(r)$ and $f_L(l)$ are the marginal probability density functions of R and L respectively, and $F_R(l_i)$ is the cumulative distribution function of the resistance variable R. The basic event probabilities labeled E_2–E_9 in the fault trees were obtained by means of Eq. (10). Although it is recognized that wind loading is a random variable whose magnitude may increase or decrease with time, current analysis and design methods for wind effects on structures (for example, Ref. [14]) generally envelope the most critical load conditions. The load effect, l, taken as deterministic, corresponds to hurricane wind design pressures obtained using the procedure of Ref. [14] for wind loading. The probability of failure of basic events which are conditional in nature are obtained through expert experience or information, as discussed subsequently in the paper.

In addition to damage propagational effects, an important wind damage phenomenon that should be considered in modeling wind damage is common-cause or common mode effects [12,15,16]. The hurricane wind affects the building envelope components at the same time and is a typical common-cause event. This introduces another level of complexity in the fault tree analysis since we can no longer make the simplifying assumption that all events are independent of each other. Noting that component failure events are generally positively correlated [17], we estimated the dependence between any two events by means of the

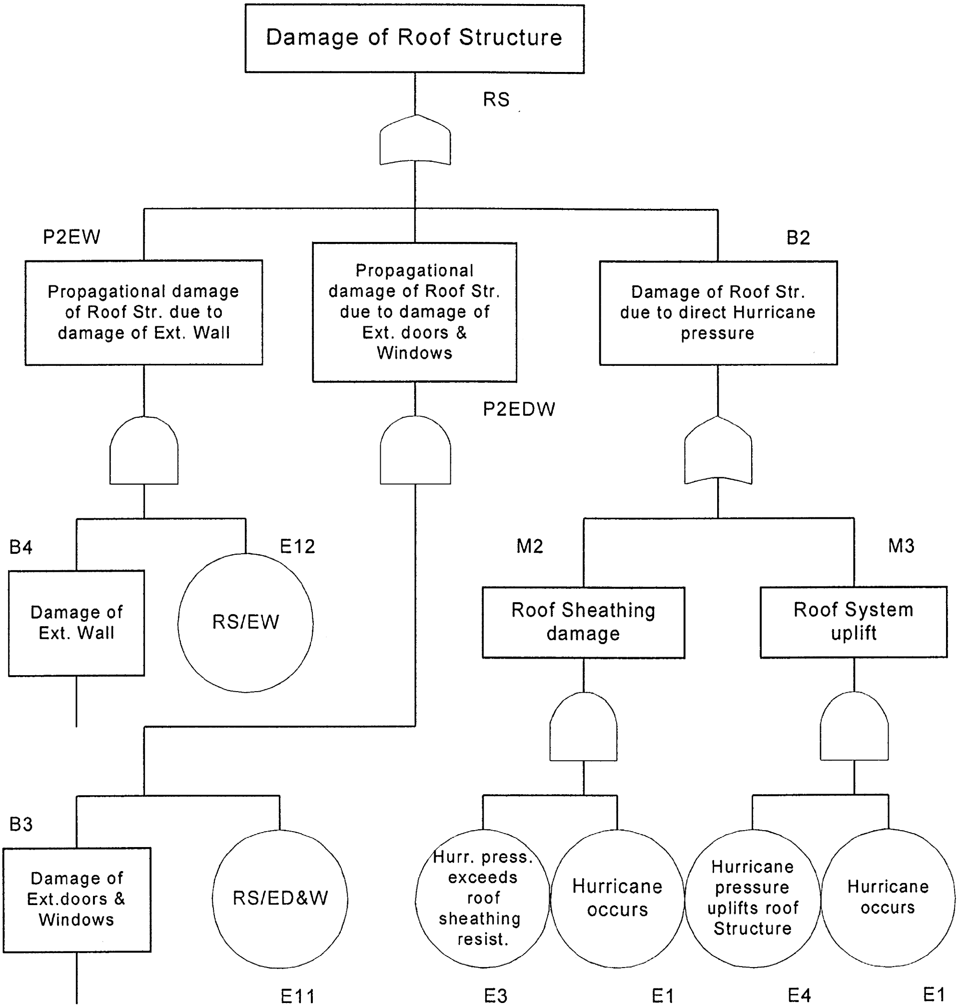

Fig. 3. Fault tree for roof structure damage.

traditional correlation coefficient [18] using the method proposed by Reed et al. [19], in the following form:

$$P(E_1E_2) = P(E_1)P(E_2) + \rho_{1,2}(\sqrt{P(E_1)P(E_2)[1 - P(E_1)][1 - P(E_2)]}). \tag{11}$$

In Eq. (11), $P(E_1E_2)$ denotes the joint probability of failure of any two events E_1 and E_2, $P(E_1)$ and $P(E_2)$ are the individual probabilities of failure of events E_1 and E_2, respectively, and $\rho_{1,2}$ is the correlation coefficient between $P(E_1)$ and $P(E_2)$.

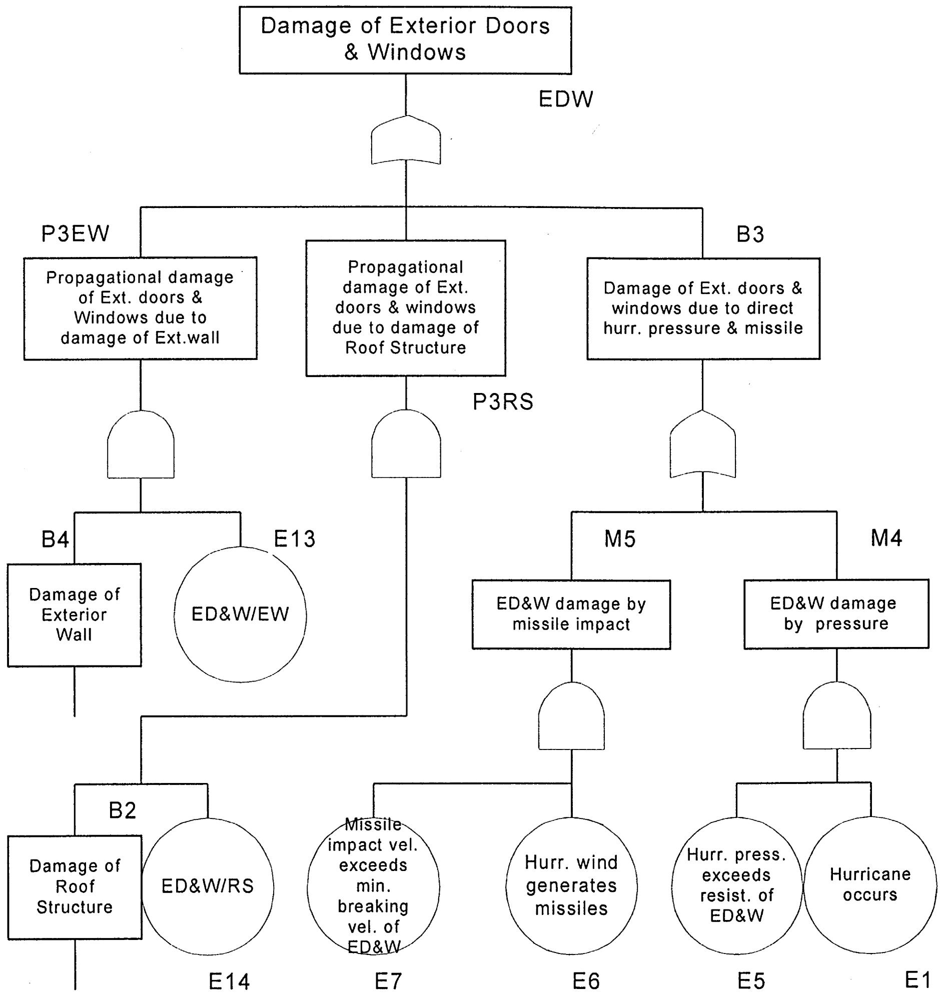

Fig. 4. Fault tree for exterior doors and windows damage.

3.1. Building interior probability of failure

The conditional probability of damage of the building interior, given component damage, P(interior damage), is obtained via a quasi-fault tree analysis (see Fig. 6). The special symbol used in the fault tree (F-OR) represents a user-defined function, which in the present case is given by

$$P(\text{interior damage}) = \sum_{i=1}^{n} [P(\text{INT}/C_i)]\text{RCF}_i, \tag{12}$$

where $P(\text{INT}/C_i)$ is the probability of interior damage given that the ith component is damaged, n the number of components used in the interior damage model, and RCF_i

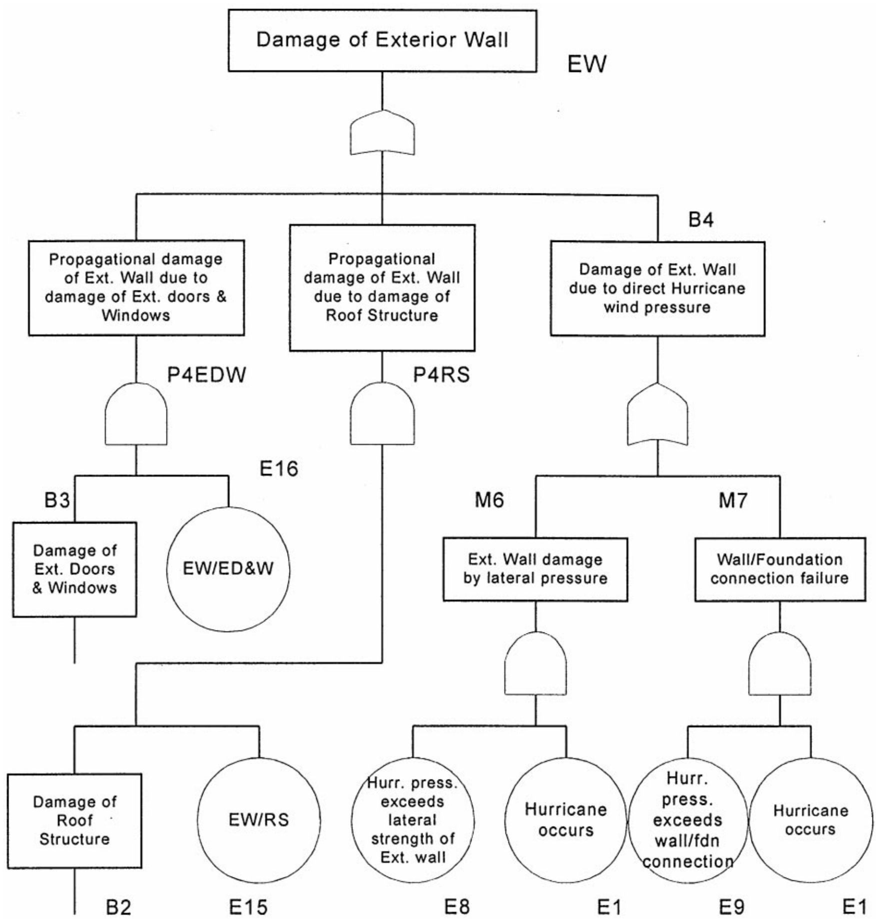

Fig. 5. Fault tree for exterior wall damage.

the relative component cost factor, given by

$$\mathrm{RCF}_i = \frac{\mathrm{CCF}_i}{\sum_{i=1}^{n}\mathrm{CCF}_i}, \tag{13}$$

in which CCF_i is the component cost factor.

3.2. Distribution functions and parameters for component resistance

Crucial steps in the damage band technique are the selection of the set of building components and connection characteristics that furnish upper and lower wind damage probabilities, and the choice of appropriate distribution functions of the failure mode resistances and of their distribution parameters. The building characteristics

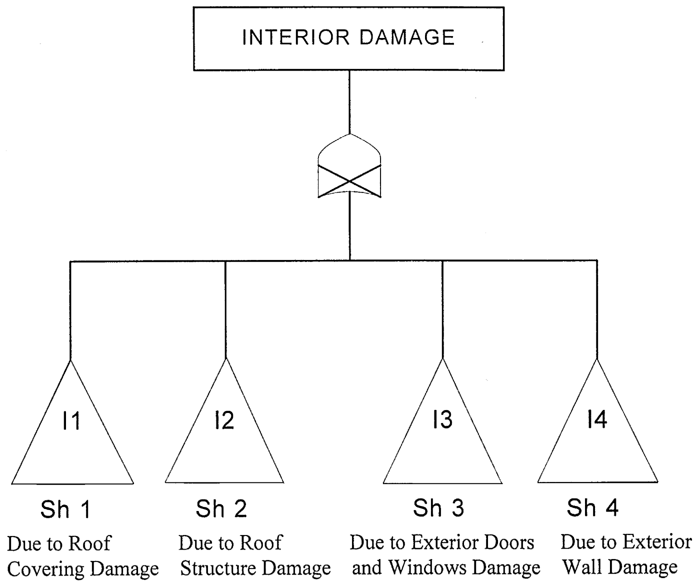

Fig. 6. Fault tree for interior damage.

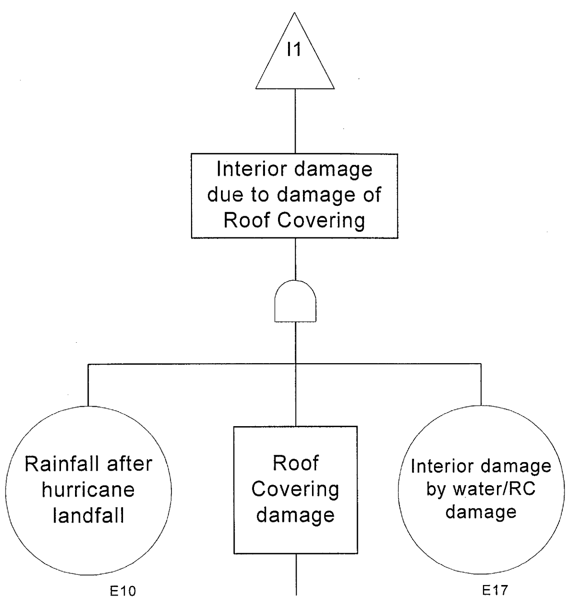

Fig. 7. Fault tree for interior damage due to roof covering damage (Sh. 1).

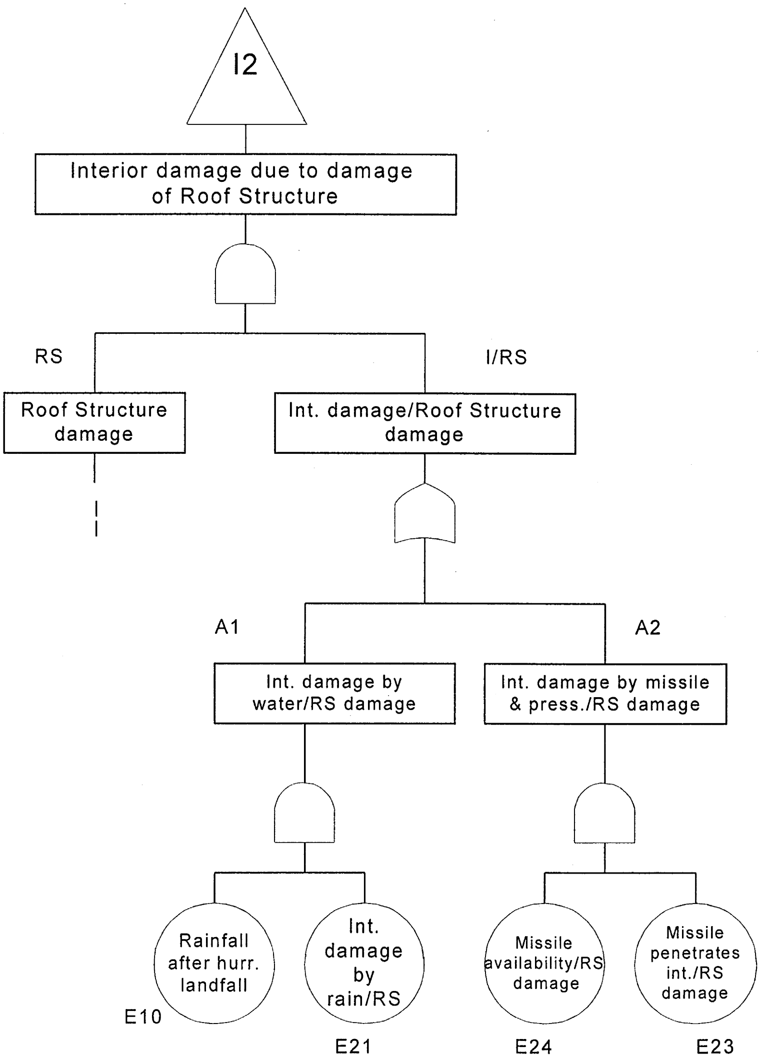

Fig. 8. Fault tree for interior damage due to roof structure damage (Sh. 2).

used for upper and lower bound fragilities are shown in Table 1. We hasten to add that the combination of building components and connection characteristics may not necessarily reflect that of any particular building. The component and connection characteristics were chosen on the basis of individual components and failure modes only, with prime concern placed upon wind damage performance, building technology, design codes, and material data.

As seen in Eq. (10), evaluation of the basic event conditional probabilities of failure of the fault trees requires use of the marginal probability density function of the

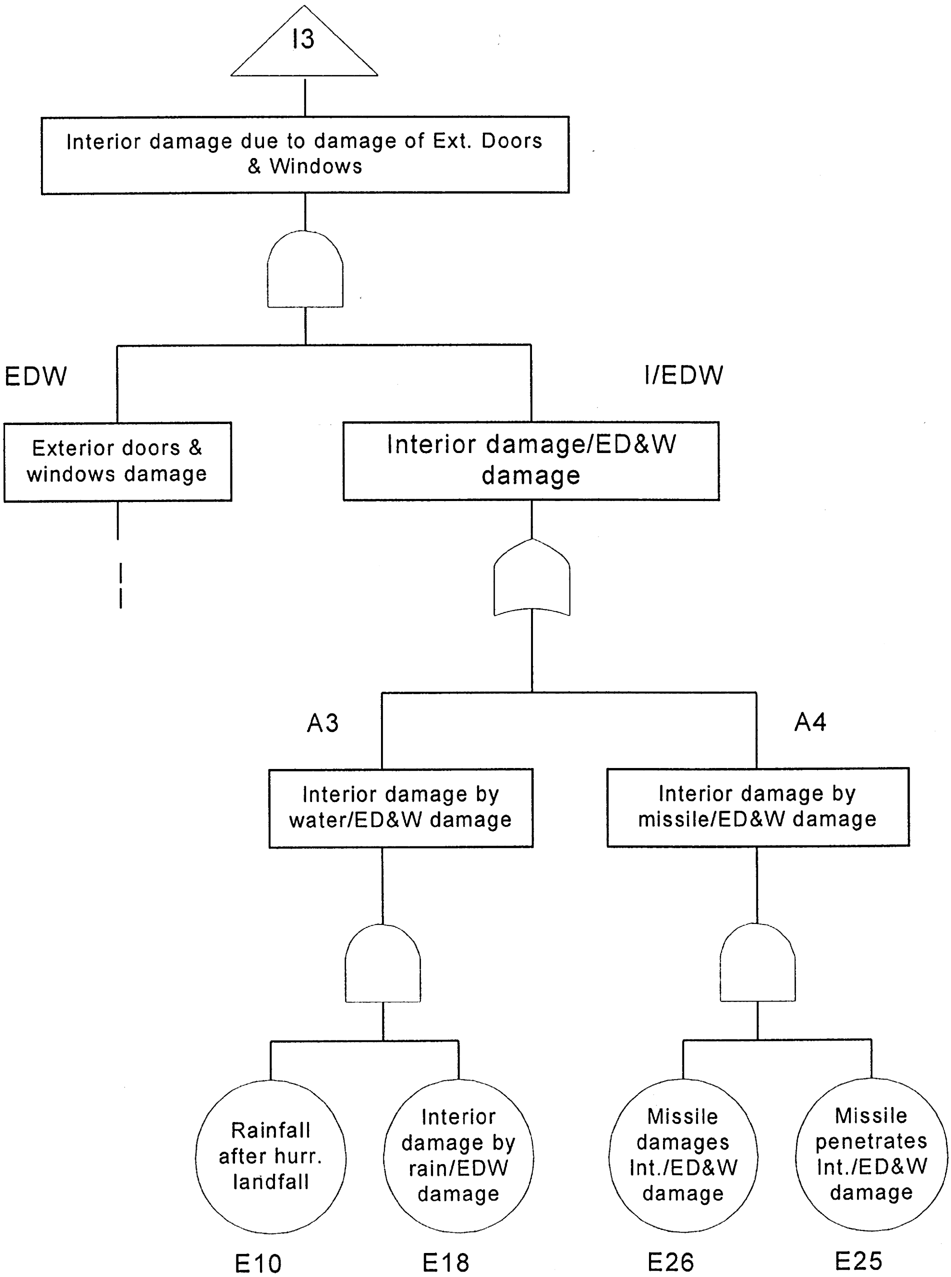

Fig. 9. Fault tree for interior damage due to exterior doors and windows damage (Sh. 3).

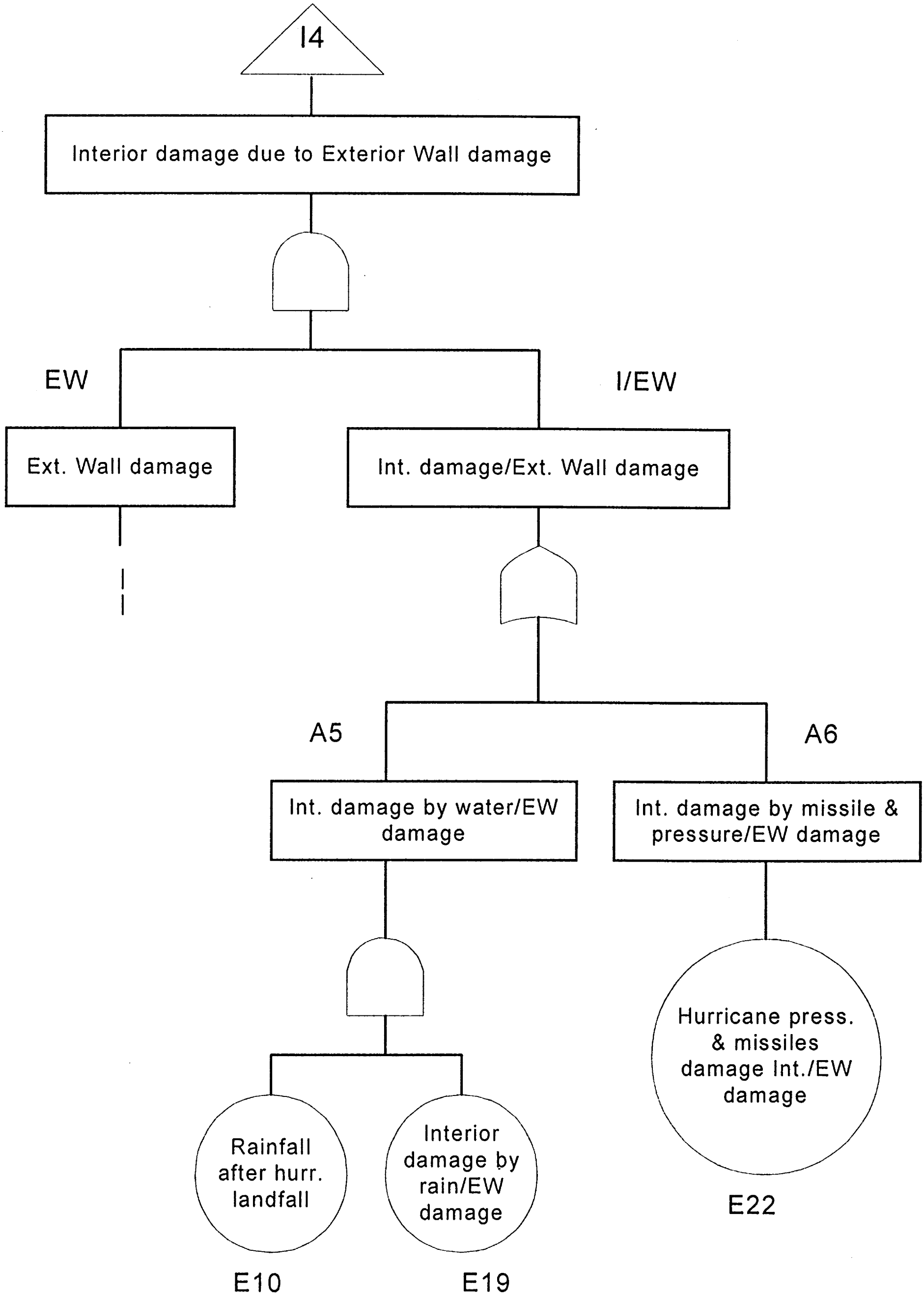

Fig. 10. Fault tree for interior damage due to exterior wall damage (Sh. 4).

Table 1
Building characteristics for upper and lower bound fragilities

Component	Failure mode modeled by	Properties for upper bound fragility	Properties for lower bound fragility
Roof covering (RC)	Blow-off at the attachments	Asphalt shingles stapled @ 12 in (300 mm) o.c.	Flat concrete tiles fastened with 6d common nails @ 6 in (150 mm) o.c.
Roof structure (RS)	Roof sheathing failure by fastener pull-out	OSB, 15/32 in (12 mm) thick, fastened with 6d common nails @ 12 in (300 mm) o.c., 24 in (600 mm) intermediate supports	Plywood, 19/32 (15 mm) in thick 5-ply, fastened with 10d common nails @ 6 in (150 mm) o.c.
	Uplift at roof-to-wall connection	Wood rafters @ 2 ft (0.6 m) o.c. toe-nailed to wall plate with 3 no. 16d box nails	Roof frame fastened to wall with no. H7 Simpson Strong Tie connector [20]
Exterior doors and windows (ED and W)	Breakage by windborne missiles	Annealed glass, 3/16 in (5 mm) thick.	Highly tempered glass, 3/4 in (19 mm) thick
	Interior surface failure by pressure	Weathered annealed glass	New fully tempered glass
Exterior wall (EW)	Lateral pressure failure	Wood stud wall, studs @ 16 in (400 mm) o.c.	Precast concrete wall
	Wall-to-foundation uplift	Connection using 3/8 in (10 mm) bolts @ 8 ft (2.4 m) o.c.	Connection using piling strap HST3 [20]
Interior (INT)	Failure of RC, RS, ED&W, EW	As per properties for RC, RS, ED&W, EW	As per properties for RC, RS, ED&W, EW

resistance variable, $f_R(r)$. The distribution types and distribution parameters corresponding to the component failure modes of Table 1 are shown in Tables 2 and 3 . In the cumulative distribution functions $\Phi(\cdot)$ of Table 2, l_i represents the load effect, μ_R and σ_R are, respectively, the mean and standard deviation of the resistance random variable R, α is the shape parameter (or Weibull slope), β the scale parameter, and c the minimum life.

In general, the form of the component failure mode resistance, $f_R(r)$, depends on the availability and form of the test data. For component failure modes where test data are available and the data are fitted to some distribution, that distribution type is adopted. If the available failure data were not fitted to a distribution, these were analyzed and fitted to an appropriate distribution. In cases where test data are available only in the form of means and variances, or where mean strengths of connections have been determined by analytical calculations, the lognormal model was adopted. Although the normal distribution is more analytically tractable and has well-known properties, it has some disadvantages as a model for material behavioral

Table 2
Probability density functions of component resistance

Component resistance	Probability distribution of component resistance	$F_R(l_i) = \Phi(\cdot)$
Roof covering uplift resistance	Lognormal	$\Phi\left[\dfrac{\ln(l_i) - \ln(m_R)}{\sigma_{\ln(R)}}\right]$
Roof sheathing Fastener pull-out resistance	Normal	$\Phi\left[\dfrac{l_i - \mu_R}{\sigma_R}\right]$
Uplift resistance of roof-to-wall connection	Lognormal	$\Phi\left[\dfrac{\ln(l_i) - \ln(m_R)}{\sigma_{\ln(R)}}\right]$
Missile impact resistance of exterior doors and windows	Lognormal	$\Phi\left[\dfrac{\ln(l_i) - \ln(m_R)}{\sigma_{\ln(R)}}\right]$
Lateral pressure resistance of glass cladding	2-parameter Weibull	$1 - \exp\left[-\left(\dfrac{l_i}{\beta}\right)^{\alpha}\right]$
Lateral pressure resistance of exterior wall	3-parameter Weibull	$1 - \exp\left[-\left(\dfrac{l_i - c}{\beta}\right)^{\alpha}\right]$
Wall-to-foundation uplift resistance	Lognormal	$\Phi\left[\dfrac{\ln(l_i) - \ln(m_R)}{\sigma_{\ln(R)}}\right]$

properties [18,43,44]. The choice of the lognormal model for the resistance cases described above was based on its widespread use in engineering practice [15,18,45,46] and its ability to dovetail some of the disadvantages of the normal distribution, while at the same time, possessing most of its good properties.

3.3. Conditional event and other probabilities

The probabilities of basic events of the fault trees which are conditional in nature and which are not obvious from wind damage experience are obtained through expert information and experience of wind and structural engineers using a Delphi approach [47]. The method involved the following steps: (1) A preliminary meeting with each expert to explain the questionnaire, i.e., the conditional probability data, and solicit responses. (2) Aggregation of the initial responses of the experts using the weighted arithmetic mean method:

$$P_i = \sum_{i=1}^{n} O_i R_i \bigg/ \sum_{i=1}^{n} R_i, \tag{14}$$

where P_i is the aggregated responses of the experts, R_i the rating of the ith expert, O_i the ith expert's estimate, and n the number of expert's. The ratings for aggregating

Table 3
Distribution parameters for component resistance

Component resistance	Distribution parameters		References
	Upper	Lower	
Roof covering uplift resistance	LN(60, 0.20)[a] (psf) (28.7,0.10) (kPa)	LN(237, 0.20)[a] (113.5,0.10)	[21–26]
Roof sheathing fastener pull-out resistance	$N(82, 12^2)$[b] (psf) $(39.3, 5.7^2)$ (kPa)	$N(254, 54^2)$[b] $(121.6, 25.9^2)$	[24,27–32]
Uplift resistance of roof-to-wall connection	LN(950, 0.17) (plf) (13.87,0.002) (kN/m)	LN(2985, 0.17) (43.6,0.00 2)	[20,21,24]
Missile impact resistance of exterior doors and windows	LN(37.5^2, 0.156)[c] (mph) (16.8^2,0.07) (m/s)	LN(80^2,0.156)[c] (35.8^2,0.07)	[33–36]
Lateral pressure resistance of glass cladding	$W(1.98$, 182 psf$)$[d,e] $W(\alpha, \beta)$ $W(1.98$, 8.72 kPa$)$	$W(2.89$, 716 psf$)$[d,e] $W(2.89$, 34.3 kPa$)$	[36–39]
Lateral pressure resistance of exterior wall	$W(34.1$ psf, 3.28, 38.8 psf$)$ $W(c, \alpha, \beta)$ $W(1.63$ kpa, 3.28, 1.86 kPa$)$	Based on (U)[f] ”	[40–42]
Wall-to-foundation uplift resistance	LN(2628, 0.20) (plf) (38.4,0.003) (kN/m)	LN(5126, 0.20) (74.8,0.003)	[20,24,31,32]

[a] Lognormal distribution.
[b] Normal distribution.
[c] Parameters based on missile impact velocities and modified for the 2×4 in timber missile.
[d] Weibull distribution.
[e] Obtained by fitting data to test results on weathered and new glass samples for upper and lower bound fragilities, respectively. Glass type factor of 4 was used for fully tempered glass.
[f] Lower bound fragility obtained by modifying upper bound parameters to account for increased strength due to high modulus of elasticity of concrete used in establishing the lower fragility curve.

the initial responses were based on the number of years of wind damage experience and damage documentation conducted by each expert. (3) Review by each expert of the aggregated initial responses, and indication of a self-rating. (4) Aggregation of new responses of the experts using Eq. (14) and the experts' self-ratings.

The final aggregated responses are shown in Table 4. Each conditional probability value in Table 4 represents the probability of failure of a building component, given that another component fails. In addition to use of self-ratings in aggregating the expert responses, the data gathering procedure ensured that the expert responses were independent of each other at each response stage. This two-stage Delphi method is considered most feasible in a time and financial constraints situation. Since building damage degree is obtained as a function of the components' damage amounts (see Eq. (7)), it is important to note that the failure probabilities in Table 4 must be tempered to account for the location, distribution, and spread of components' damage in windstorms (i.e., damage localization of components). This is effected by use of component

Table 4
Conditional probability data

Conditional event	Hurricane intensity[a] in mph (m/s) Cat. 1 74–95 (33–42)	Cat. 2 96–110 (43–49)	Cat. 3 111–130 (50–58)	Cat. 4 131–155 (59–69)	Cat. 5 > 155 (> 69)
Roof structure/exterior wall	0.37	0.46	0.61	0.73	0.85
Roof structure/exterior doors & windows	0.33	0.42	0.57	0.69	0.82
Exterior wall/roof structure	0.16	0.25	0.38	0.51	0.65
Exterior wall/exterior doors & windows	0.21	0.33	0.45	0.60	0.75
Exterior doors & windows/roof structure	0.60	0.64	0.71	0.78	0.90
Exterior doors & windows/exterior wall	0.70	0.80	0.85	0.89	0.93
Rainfall/hurricane occurrence	0.94	0.94	0.94	0.94	0.94
Interior damage by rain/roof covering damage	0.50	0.54	0.63	0.78	0.90
Interior damage by rain/exterior wall damage	0.76	0.81	0.86	0.93	0.95
Interior damage by rain/exterior doors & windows damage	0.74	0.79	0.84	0.88	0.92

[a] 1-min mean speeds.

location parameters (see following section) to obtain actual component damage probabilities.

The failure probabilities of events E_{20}–E_{22}, and E_{24} are obvious from wind damage experience and are taken equal to one. $P(E_{26})$ is estimated from $P(E_7)$ while $P(E_{23})$ and $P(E_{25})$ are estimated from the ratio of the average area of the respective components to that of the building envelope.

4. Component location parameter and cost factors

As previously stated, component location parameter, α_i, accounts for the location and distribution of building components in relation to their degrees of wind damage. The expert-supplied failure probabilities of Table 4 represent the probabilities of any damage to a building component, akin to the binary modeling of faults in classical reliability analysis, i.e., operational or non-operational. A building component may consist of several items and may also be found at different locations on a building. Moreover, these different locations where a component may be found, may have different exposures to the wind effects. Wind flow phenomena such as flow separation and the associated wake turbulence experienced by the bluff form of a building may also contribute to localization of building components' damage. Hence components' failure in windstorms is usually localized, and failure of one item of a component does not necessarily imply total damage of the component. In general, building components fail in windstorms in "degrees". Component location parameters were obtained via expert experience using the Delphi procedure previously described. The component location parameters, as a function of the sustained 1-min wind speeds, V, are

$$\text{Roof covering: } \alpha = 2.264612 - 0.067645V + 0.000666V^2 - 1.841 \times 10^{-6}V^3 \tag{15a}$$

$$\text{Roof structure: } \alpha = 0.046451 - 0.00668V + 0.000129V^2 - 3.94 \times 10^{-7}V^3, \tag{15b}$$

$$\text{Ext. doors \& windows: } \alpha = 0.592731 - 0.029062V + 0.000366V^2 - 1.104 \times 10^{-6}V^3, \tag{15c}$$

$$\text{Exterior wall: } \alpha = -0.174995 - 0.005124V + 0.000134V^2 - 4.44 \times 10^{-7}V^3, \tag{15d}$$

$$\text{Building interior: } \alpha = 1.394525 - 0.044214V + 0.000454V^2 - 1.247 \times 10^{-6}V^3. \tag{15e}$$

Component cost factors, defined as the ratio of replacement value of a component to the replacement value of the building, objectively relate individual component damage degrees to the damage degree of the entire building. The component cost factors used in developing the damage bands in this work were evaluated on the basis of the model buildings in Ref. [48–50]. The cost of contents for each building was estimated as a percentage of the building's replacement value, following the general guidelines in Ref. [51]. The average values of the cost factors, using six, thirteen, eight, and four types of model residential, commercial/industrial, government/institutional, and 4–10 story buildings, respectively, are shown in Table 5. The relative component cost factors, RCF_i (see Eq.(13)) used in the interior damage probability evaluation were based on the average values of the cost factors given in Table 5. The resulting values of RCF_i are shown in Table 6.

Table 5
Average building component cost factors

Component	1–3 story residential	1–3 story commercial/ industrial	1–3 story govt./ institutional	4–10 story mid-rise
Structural System	5.4	2.9	3.8	13.1
Roof covering	1.4	1.8	1.5	0.4
Roof structure	2.7	4.1	3.3	3.0
Exterior wall	9.7	8.6	9.6	9.6
Exterior doors & windows	3.8	2.6	1.9	1.5
Building interior	71.9	75.6	76.5	71.0

Table 6
Relative component cost factors

Component	Cost factor	Relative cost factor
Roof covering	1.5	0.09
Roof structure	3.5	0.21
Exterior doors and windows	2.5	0.15
Exterior wall	9.2	0.55
Total	16.7	1.00

5. Damage bands

The fault trees were evaluated using Eqs. (8)–(14) and the data of Tables 1–4, to obtain component failure probabilities. In conjunction with the component cost data of Tables 5 and 6, and the component location parameter equations 15, upper and lower building damage degrees were obtained using Eq. (7). Evaluation of the fault trees and subsequent calculation of the damage degrees was found to be most efficiently implemented on several spread sheet files that were linked to one another. In applying (7), we have conservatively allowed for structural system damage probabilities in low-rise buildings equal to the corresponding damage probabilities of the exterior walls. Also, in view of the use of shear walls, and better design attention in mid-rise building contruction, additional considerations were made in establishing the damage bands for mid-rise buildings. These are the use of reinforced concrete and steel roof structures for the lower and upper bound fragilities, respectively, and exterior walls that are two times less likely to be damaged than those of low-rise buildings. Within the context of the damage band concept, these assumptions are considered conservative and reasonable.

The resulting upper and lower damage functions defining the damage bands were subsequently fitted to polynomial regression models and 95% confidence bounds on the predicted damage degrees found using the test statistic [52]:

$$\mathrm{DD}/l \pm t_{\alpha/2} S\sqrt{l_0'(L'L)^{-1}l_0}. \tag{16}$$

In Eq. (16), $t_{\alpha/2}$ is the appropriate point on the T_{n-k-1} distribution, and $S\sqrt{l_0'(L'L)^{-1}l_0}$ is the standard error of prediction. The resulting damage bands are shown in Figs. 11–14, respectively, for 1–3 story residential, commercial/industrial, government/institutional buildings, and 4–10 story mid-rise buildings, in terms of the equivalent sustained 1-min hurricane wind speeds.

To obtain an indication of the robustness and validity of the present work, the damage bands were subsequently compared to the vulnerability relationships for single family dwellings presented in Sparks and Bhinderwala [7] for hurricane winds, and also to the mean percent–wind speed relationships presented in Hart [5] for wood, concrete or masonry, and steel buildings impacted by tornadoes. For consistency, the gradient wind speeds used in Ref. [7] have been converted to the equivalent

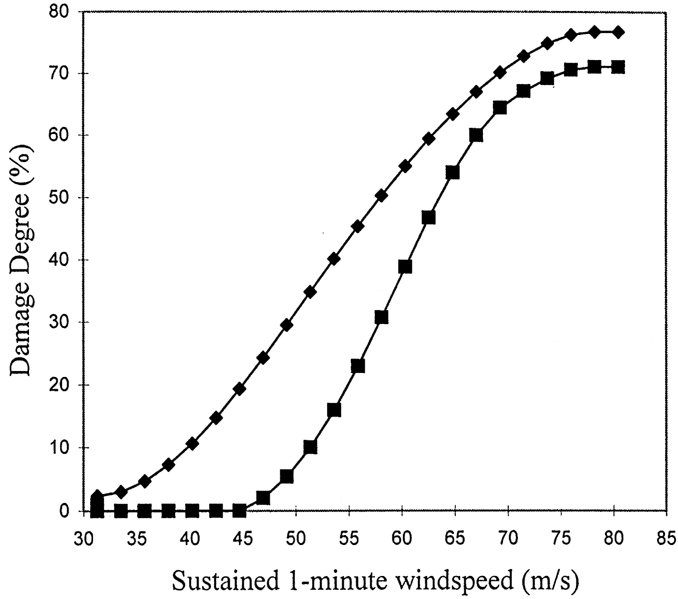

Fig. 11. Wind damage band for 1–3 story residential buildings. ♦ Upper, ■ lower.

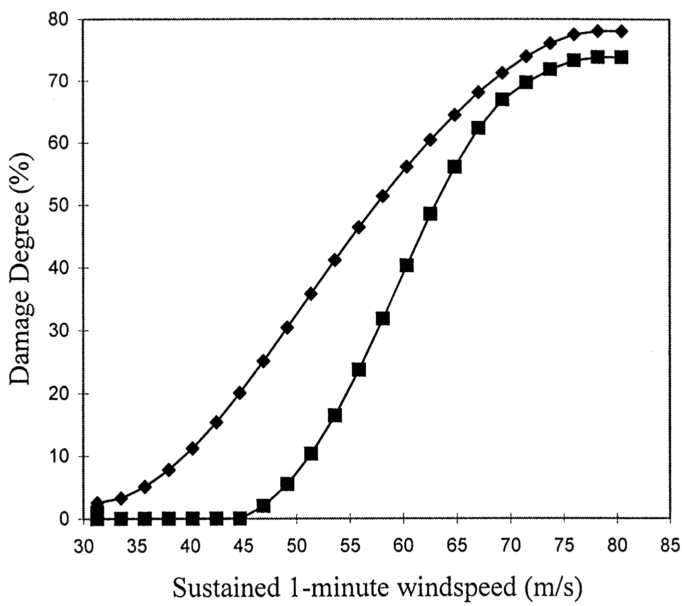

Fig. 12. Wind damage band for 1–3 story commercial/industrial buildings. ♦ Upper, ■ lower.

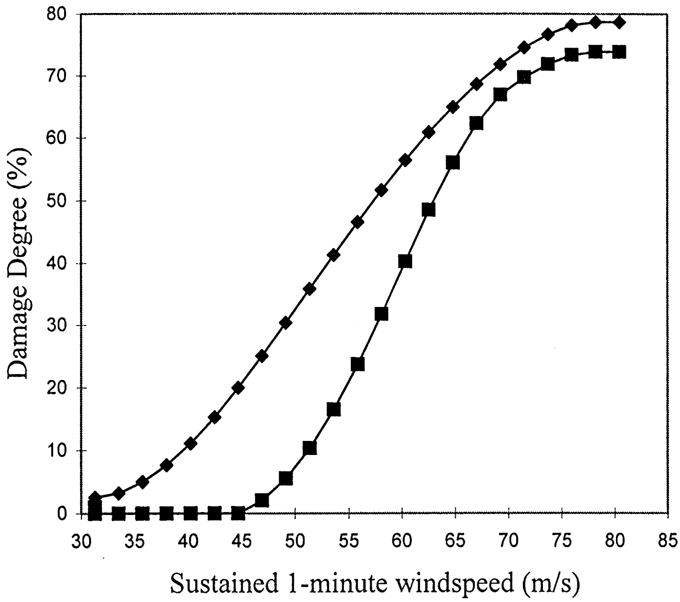

Fig. 13. Wind damage band for 1–3 story institutional buildings. ♦ Upper, ■ lower.

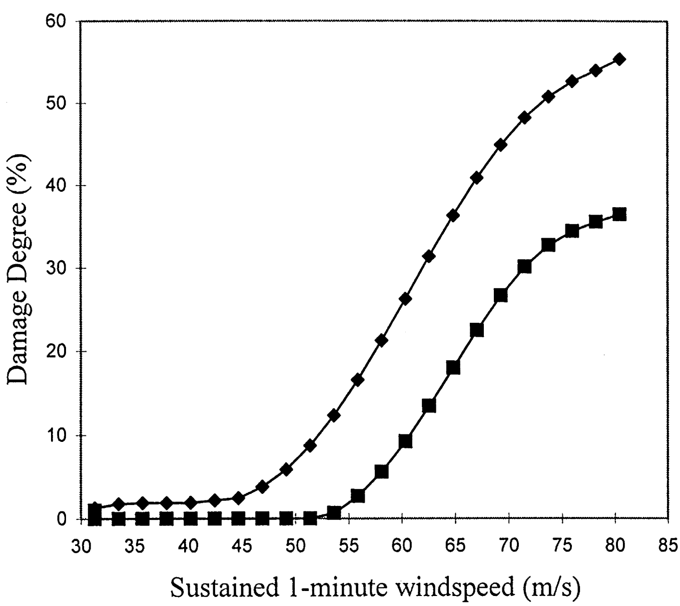

Fig. 14. Wind damage band for 4–10 story mid-rise buildings. ♦ Upper, ■ lower.

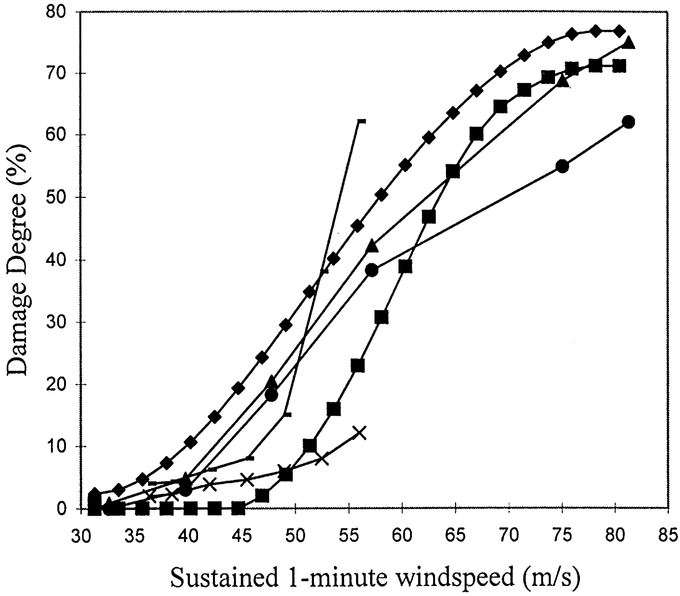

Fig. 15. Comparison of damage predictions for residential buildings. ♦ Author (upper), ■ author (lower), ▲ Hart (wood), ● Hart (concrete), ▬ Sparks (overall loss), × Sparks (direct damage).

sustained 1-min surface winds using a conservative factor of 0.70 [8,53]. The result of the comparison is shown in Fig. 15.

The wind damage resistance of the building types in Ref. [5] may be considered as spanning the spectrum of building wind damage resistivity, and hence can be compared to the damage bands reported herein. To undertake this comparison, it was necessary to convert the tornado wind speeds to the equivalent 1-minute hurricane speeds. Since the appearance of damage to structures in windstorms of the same intensity is the same, regardless of the type of storm [54,55], application of the damage matrices in Ref. [5] to tornado damage, does not in practice, detract from the use of the same for other extreme windstorms such as hurricanes. Conversion of the tornado windspeeds to the equivalent hurricane 1-min winds was made by first converting the tornado speeds to the corresponding peak gust speeds using the procedure outlined in Fujita [56], and then converting the resulting hurricane peak gust speeds to 1-min speeds using the gust factor/averaging time relationship for hurricane winds [57]. The upper and lower damage functions from the present work, indicated as Author, and the mean damage curves in Ref. [5] are presented in the same graphs (see Figs. 15–17) for comparison.

In general, it is seen that for the wind speed range of interest in this work, the mean damage curves in Ref. [5] and the vulnerability curves of Ref. [7] furnish damage percentages smaller than the upper bound values from the present research, i.e., the upper damage functions of the present work furnish upper threshold damage percentages. Above a wind speed of about 53 m/s, the overall loss ratios in Ref. [7] appear to

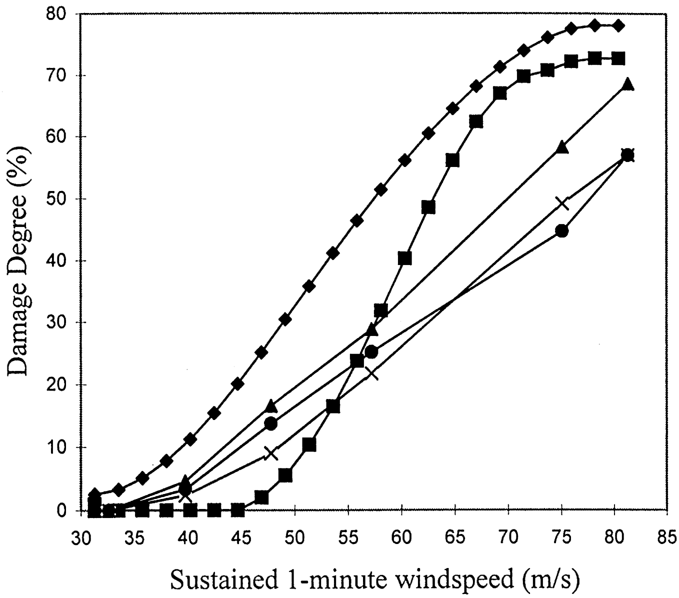

Fig. 16. Comparison of damage predictions for commercial buildings. ♦ Author (upper), ■ author (lower), ▲ Hart (wood), ● Hart (concrete), × Hart (metal).

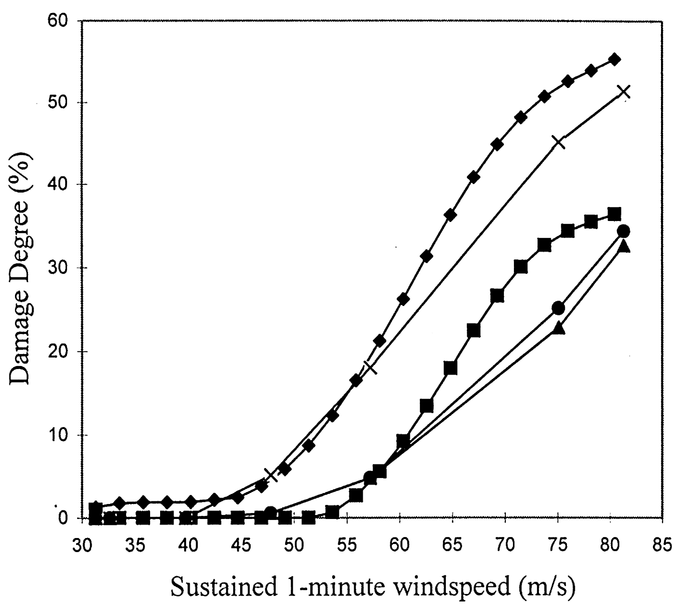

Fig. 17. Comparison of damage predictions for buildings four or more stories high. ♦ Author (upper), author (lower), ● Hart (concrete with shear wall), × Hart (concrete without shear wall), ▲ Hart (steel frame).

be greater than the damage percentages furnished by the upper damage function developed herein. This is because the overall loss ratio in [7] included such items as payments for additional living expenses and debris removal, which are not included in the calculation of probable maximum loss. Also, because the direct damage ratio in Ref. [7] did not include loss to contents, the lower damage function presented herein predicts higher damage percentages than the direct damage curve in Ref. [7] for wind speeds between 50 and 56 m/s.

In the lower windspeed regimes (i.e., up to category 3 hurricane intensity), the lower damage functions developed herein furnish lower threshold damage percentages than those in Ref. [5], but beyond this wind regime, the mean damage percentages in Ref. [5] become lower than the predictions of the current study. In the higher wind regimes, the slopes of the damage curves for concrete and steel in Ref. [5] either decrease or do not increase rapidly as would be expected by virtue of wind damage being indirectly proportional to the second power of the wind speed. This fact, coupled with the wholly subjective nature of the damage matrices [5] may account for this part of the mean damage curves in Ref. [5] falling outside the building damage bands presented herein.

6. Significance of wind damage bands

Building wind damage bands are developed for specific classes (or types) of buildings as depicted in Figs. 11–14. The upper and lower damage degree–windspeed relationships (otherwise known as damage functions) define the boundaries of a damage band. The band so defined contains the damage functions for all buildings in the occupancy class for which the damage band was developed. The upper boundary of a damage band can be thought of as representing the wind damage function of the least wind-resistant building in that occupancy class. Conversely, the lower boundary of a damage band corresponds to the damage function of the most wind-resistant building for the building occupancy class. This information is vital for the damage prediction of individual buildings. Building damage bands are employed with building attributes to determine the wind damage vulnerability of individual buildings, groups of buildings, and for wind damage mitigation. The attributes of a given building determine the damage function of that building, which lies between the upper and lower boundaries of the damage band for that building class.

7. Discussion and conclusions

From the building damage bands (Figs. 11–14), it is seen that the wind damage functions are non-linear, a behavior that had previously been noted by analysis of past wind loss data [6,7]. For all three occupancy classes of 1–3 story buildings, the greatest differences in the damage degrees furnished by the upper and lower damage functions occur in the 43–60 m/s wind speed range. The implication is that the differences in the damage response of individual 1–3 story buildings are most evident in the 43–60 m/s wind regime. In contrast, the corresponding wind speed range for mid-rise buildings is 54–81 m/s, with the damage response of individual mid-rise buildings being most easily distinguished in the category 5 hurricane wind regime (i.e., windspeeds greater than 69.3 m/s).

The damage bands for 1–3 story buildings also clearly indicate that at very high wind speeds (category 5 winds), the upper and lower damage functions tend to approach each other, i.e., the difference in damage response of the most wind-resistant and the least wind-resistant building becomes insignificant. In practical terms, a 1–3 story building exposed to such wind regimes experiences a near-total destruction to its envelope. In contrast, mid-rise buildings do not experience near-total destruction to their envelopes. A much higher wind regime than used in this study would be necessary to cause near-total destruction to the superstructure of mid-rise buildings. The damage bands also indicate that no significant damage will occur to the best quality building experiencing windspeeds less than or equal to 47 and 56 m/s for low- and mid-rise buildings, respectively.

When placed side by side (see Fig. 18), the damage bands for 1–3 story residential, commercial, and institutional buildings do not show any pronounced differences in peak values of damage degree. Since differences in building occupancy classes are reflected in the present model in terms of component cost factors, a much larger population of buildings of each occupancy class than used in this study would be necessary to conclusively determine if any systematic differences exist in the damage bands for the three occupancy classes of low-rise buildings. However, it is to be noted

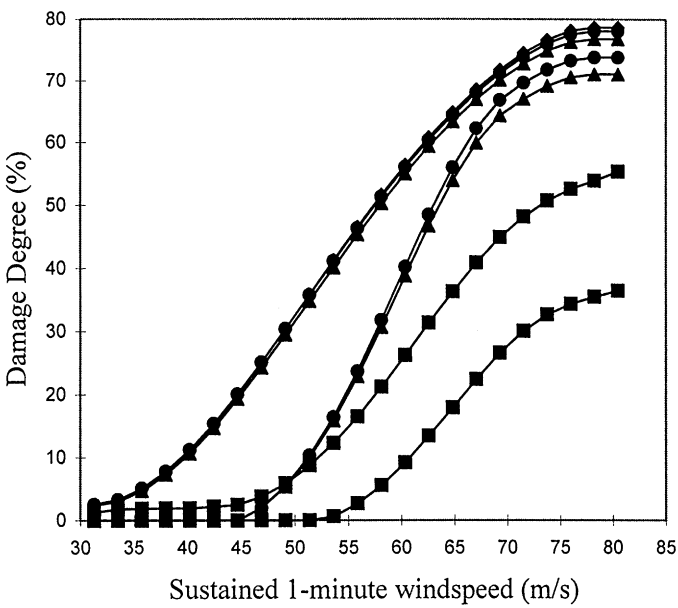

Fig. 18. Comparison of wind damage bands for different types of buildings. ■ Mid-rise, ▲ residential, ● commercial, ♦ institutional.

that the damage bands were obtained on the basis of average cost factors for each building occupancy class. Obviously, variations exist in the values of component cost factors for individual types of buildings within an occupancy class. The decision to use damage bands obtained on the basis of building occupancy classes or on the basis of a particular type of building within an occupancy class depends on the application. Since a damage band is ultimately used in conjunction with the relative resistivities of buildings for predicting the damage to individual buildings and groups of buildings, it is recommended that damage bands based on the cost factors of the specific type of building under consideration be used in determining individual building damage degree rather than the cost factors for the building's occupancy class. For portfolio analysis, however, damage bands based on average cost factors of building occupancy classes are recommended.

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