DEVELOPMENT OF A WIND DAMAGE AND DISASTER RISK MODEL FOR SOUTH AFRICA

by

Adam M W Goliger

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Supervisors
Prof J V Retief
Prof H-J Niemann (Ruhr Universität, Bochum, Germany)

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I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and has not previously, in its entirety or in part, been submitted for a degree.

Adam M W Goliger

28th day of October 2002
ABSTRACT

This dissertation presents the development process of a wind damage and disaster management support model for South Africa. Several aspects of wind damage are analysed. The impact of wind disasters on human habitat is highlighted by providing selected data of loss due to such events. This is followed by a comprehensive review of relevant research, carried out locally and internationally. The role and relevance of wind loading codification is discussed.

The factors influencing wind damage are identified and their applicability to South African conditions is evaluated. An outline of a database of wind damage in South Africa which has been developed during the course of the project is presented. Selected statistics derived from this database are presented.

A probabilistic model for assessing wind damage in South Africa is proposed. The model is based on the spatial principle of occurrence of strong wind events. A 'first approximation' division of the country into zones where various types of wind events occur and the characteristics of their generic footprints (i.e. distribution of wind speeds) are developed. The risk model procedure also takes the distribution of wealth, and the vulnerability of the built environment into account.
OORSIG

Hierdie verhandeling bied die ontwikkelingsproses vir 'n hulpmodel vir windskade en rampbestuur vir Suid Afrika aan. Verskeie aspekte van windskade word ontleed. Die invloed van windskade op woongebiede word beklemtoon deur die aanbieding van geselekteerde data oor relevante plaaslike en internasionale navorsing. Die rol en toepaslikheid van windbelasting in ontwerpkodes word bespreek.

Die faktore wat windskade beïnvloed, word geïdentifiseer en die aanwendbaarheid onder Suid Afrikaanse onstandighede word beoordeel. 'n Beskrywing van 'n databasis vir windskade in Suid Afrika, wat tydens die projek saamgestel is, word aangebied. Sekere statistiek wat uit die databasis afgelei is, word voorgelê.

'n Statistiese model vir die beraming van windskade in Suid Afrika word voorgestel. Die model is gebaseer op die ruimtelike beginsel van voorkoms van sterk-wind-gebeurlikhede. 'n "Eerste benadering" – indeling van die land in streke waar verskillende soorte windgebeurlikhede voorkom en hulle karakteristieke kenmerke (byv. verspreiding van windspeed) is ontwikkel. Die werkwyse vir die risikomodel neem die verdeling van rykdom en die kwesbaarheid van die beboude omgewing in ag.
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# TABLE OF CONTENTS

ABSTRACT .......................................................................................................................... i  
OORSIG.............................................................................................................................. i  
Acknowledgements ............................................................................................................ ii  

1  INTRODUCTION ............................................................................................................. 1.1  

2  WINDSTORM DISASTERS............................................................................................... 2.1  
2.1 International perspective ............................................................................................. 2.1  
2.2 International Decade for Natural Disaster Reduction (IDNDR) ................................. 2.2  
2.3 Wind disasters in South Africa ................................................................................. 2.3  
2.4 Disaster planning ....................................................................................................... 2.4  

3  RESEARCH INTO WIND DISASTERS............................................................................ 3.1  
3.1 Site investigations and documentation ...................................................................... 3.1  
3.2 Analysis of damage .................................................................................................... 3.14  
3.2.1 Structural aspects .................................................................................................. 3.20  
3.3 Statistics of damage to structures ............................................................................ 3.22  
3.4 Economic implications .............................................................................................. 3.23  
3.4.1 National scale ....................................................................................................... 3.23  
3.4.2 Relative scale ....................................................................................................... 3.25  
3.4.3 Insurance industry ............................................................................................... 3.25  
3.4.3.1 Insurance cover ............................................................................................... 3.26  
3.4.3.2 Vulnerability function ...................................................................................... 3.27  
3.5 Prediction of damage and risk models ..................................................................... 3.29  
3.5.1 Scenarios of damage .............................................................................................. 3.32  
3.5.2 Categorising the structures ................................................................................. 3.32  
3.6 Construction guidelines ............................................................................................ 3.36  
3.7 Reconstruction and repair ......................................................................................... 3.42  
3.8 Policies ...................................................................................................................... 3.43  

4  CODIFICATION OF WIND LOADING FOR STRUCTURAL DESIGN ..................... 4.1  
4.1 Role and applicability of wind loading codes .......................................................... 4.1  
4.2 Principles and international perspective ................................................................... 4.2  
4.3 South African wind loading specifications .............................................................. 4.3  
4.4 The relevance of wind codification to South African conditions ............................. 4.4  

Page iv
## FACTORS THAT INFLUENCE WIND DAMAGE

### 5.1 Classification of severe storms

### 5.2 Characteristics of extreme winds

#### 5.2.1 Magnitude of wind speed

#### 5.2.2 Duration

#### 5.2.3 Wind speed probability of occurrence

#### 5.2.4 Geographical distribution

#### 5.2.5 Spatial extent of wind events

#### 5.2.6 Changes with elevation

#### 5.2.7 Seasonal variations

#### 5.2.8 Directional characteristics

### 5.3 Local and terrain factors affecting the wind field

#### 5.3.1 Topography

#### 5.3.2 Other structures

### 5.4 Distribution of assets

### 5.5 Resistance of structures

#### 5.5.1 Formal and informal development

#### 5.5.2 Formal structures

##### 5.5.2.1 Planning and design

##### 5.5.2.2 Approval

##### 5.5.2.3 Construction

#### 5.5.3 Informal structures

##### 5.5.3.1 Locality

##### 5.5.3.2 Density and shielding

##### 5.5.3.3 Geometrical form

##### 5.5.3.4 Permeability of roofs

##### 5.5.3.5 Fixing of sheeting

##### 5.5.3.6 Extent of unsupported surfaces and walls

### 5.6 Mechanisms of failure and extent of damage

#### 5.6.1 Content of the built environment

#### 5.6.2 Long- and short-term loading

#### 5.6.3 Large and engineered structures

#### 5.6.4 Low-rise and residential structures

##### 5.6.4.1 Minor damage

##### 5.6.4.2 Substantial damage

##### 5.6.4.3 Serious damage
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3.7</td>
<td>Zone 7: mid-latitude low</td>
<td>8.5</td>
</tr>
<tr>
<td>8.4</td>
<td>Occurrence of wind events, overlaps and anomalies</td>
<td>8.5</td>
</tr>
<tr>
<td>9</td>
<td>DEVELOPMENT OF GENERIC FOOT-PRINTS AND OCCURRENCE RATE</td>
<td>9.1</td>
</tr>
<tr>
<td>9.1</td>
<td>Background discussion on wind speed foot-prints of wind events</td>
<td>9.1</td>
</tr>
<tr>
<td>9.2</td>
<td>Thunderstorms (Zones 1-3)</td>
<td>9.2</td>
</tr>
<tr>
<td>9.2.1</td>
<td>Proposed methodology</td>
<td>9.2</td>
</tr>
<tr>
<td>9.2.2</td>
<td>Peak wind speed and reflectivity</td>
<td>9.5</td>
</tr>
<tr>
<td>9.2.3</td>
<td>Generic footprints of wind speeds</td>
<td>9.7</td>
</tr>
<tr>
<td>9.3</td>
<td>Extreme wind events: tornadoes and downbursts (Zone 3)</td>
<td>9.10</td>
</tr>
<tr>
<td>9.4</td>
<td>Frontal / coastal winds (Zones 4-7)</td>
<td>9.11</td>
</tr>
<tr>
<td>9.5</td>
<td>Occurrence rates</td>
<td>9.12</td>
</tr>
<tr>
<td>9.5.1</td>
<td>Thunderstorms (Zones 1-3)</td>
<td>9.12</td>
</tr>
<tr>
<td>9.5.2</td>
<td>Frontal / coastal winds (Zones 4-7)</td>
<td>9.15</td>
</tr>
<tr>
<td>9.6</td>
<td>Summary</td>
<td>9.16</td>
</tr>
<tr>
<td>10</td>
<td>HUMAN BUILT DEVELOPMENT</td>
<td>10.1</td>
</tr>
<tr>
<td>10.1</td>
<td>The relevance of spatial distribution / extent</td>
<td>10.1</td>
</tr>
<tr>
<td>10.2</td>
<td>Distribution of development / assets</td>
<td>10.2</td>
</tr>
<tr>
<td>10.2.1</td>
<td>Population distribution</td>
<td>10.2</td>
</tr>
<tr>
<td>10.2.2</td>
<td>Distribution of assets</td>
<td>10.2</td>
</tr>
<tr>
<td>10.2.3</td>
<td>Informal development</td>
<td>10.4</td>
</tr>
<tr>
<td>10.2.4</td>
<td>Distribution of economic activities</td>
<td>10.5</td>
</tr>
<tr>
<td>10.3</td>
<td>Replacement costs per unit area</td>
<td>10.7</td>
</tr>
<tr>
<td>10.4</td>
<td>Vulnerability curves</td>
<td>10.7</td>
</tr>
<tr>
<td>11</td>
<td>APPLICATION EXAMPLE OF THE MODEL</td>
<td>11.1</td>
</tr>
<tr>
<td>11.1</td>
<td>Distribution of human built development and wealth</td>
<td>11.1</td>
</tr>
<tr>
<td>11.2</td>
<td>Areas of development densities</td>
<td>11.5</td>
</tr>
<tr>
<td>11.3</td>
<td>Occurrence of strong wind events</td>
<td>11.5</td>
</tr>
<tr>
<td>11.4</td>
<td>Areas subject to threshold wind speeds</td>
<td>11.6</td>
</tr>
<tr>
<td>11.5</td>
<td>Wind speed rate of occurrence</td>
<td>11.8</td>
</tr>
<tr>
<td>11.6</td>
<td>Total areas subject to wind speed ranges</td>
<td>11.9</td>
</tr>
<tr>
<td>11.7</td>
<td>Vulnerability curves</td>
<td>11.12</td>
</tr>
<tr>
<td>11.8</td>
<td>Accumulated loss per km$^2$</td>
<td>11.13</td>
</tr>
<tr>
<td>11.9</td>
<td>Estimation of total loss</td>
<td>11.14</td>
</tr>
</tbody>
</table>
Chapter 1
1 INTRODUCTION

Throughout the world, as well as in South Africa, wind forms one of the dominating environmental loadings affecting structural design, and is also responsible for a large percentage of disastrous events in the built-up environment.

The issue of wind damage becomes even more relevant in view of the constant pursuit of more economic designs of structures and the development of materials with higher strength, which in many cases leads to the development and use of lighter components and also the introduction of "leaner" design techniques. (In addition, in South African conditions, buildings and facilities that do not comply with building regulations pose particular challenges to wind disaster management.)

In view of these technological trends, a significant amount of theoretical and experimental research has been carried out throughout the world into the effects of wind on structures and ways to increase their wind resistance, and therefore to minimise the amount of damage.

Despite these efforts, insurance statistics suggest that losses due to windstorm disasters continue to rise (Berz, 1991; MunichRe, 1990). This could partly be attributed to an increase in the extent of the built environment, but it also raises questions as to the possibility of global environmental change leading to an increase in severe windstorms (Kasperski, 1999; Stansfield, 2001). The situation also suggests that the scientifically derived knowledge on wind-resistant structural design has not yet been implemented across the entire construction sector. Some attempts to bridge the gap between scientific work, structural design and actual construction have been made in various countries (mainly the USA, Australia and certain parts of Europe e.g. Minor and Mehta, 1979; Reardon, 1980; Gandemer and Moreau, 1999) but not in South Africa.

There are no statistics on windstorm disasters in South Africa and a database on wind disasters has been set up at the CSIR (Goliger, 2000) as a part of the current project. The initial statistics derived from this database indicate a trend in which the number of damage events reported and their socio-economic impact is increasing.

The South African disaster management authorities do not have any system in place to assess and quantify the effects of damaging wind events. Furthermore there is no mechanism which would enable them to anticipate the likelihood and socio-economic impact of potential future events. There is no information on the spatial scale and relationships
between likely devastating wind events and the geographical extent of critical amenities, communities, administrative districts, regions and provinces.

The objective of the current dissertation is to develop a generic wind damage model to support disaster management activities in South Africa. From a national perspective, one of the most important factors affecting the costs of total loss and the associated socio-economic implications, is the extent of the land that is potentially subjected to damaging winds. A spatial statistical approach was therefore adopted in the current study.

Because of the informal and low-cost component of the built environment in South Africa, a large portion of damage occurs at wind speeds substantially lower than those stipulated by the design codes of practice, and such wind speeds occur more frequently than the extreme wind speeds referred to in the codes of practice.

In view of the above, the proposed approach does not concentrate on defining the probability of occurrence of extreme winds at a specific point (which is most relevant for the design of individual structures) but rather on assessing the spatial extent and rate of occurrence of various types of damaging winds within various regions of South Africa. The integration of such information, in combination with the data on the wind vulnerability of structures, enables one to assess the magnitude of potential loss for a specific region or district. The model considers all types of human built developments and amenities which include: formal structures, buildings and other developments exposed to wind action and damage (e.g. informal human shelter and structures, walls, fences, street signage, car shelters etc.).

International and South African perspectives on windstorm disaster are presented first and their relevance to disaster planning activities is highlighted. A review of international (and local where available) research on wind disaster is given and this is followed by a critical evaluation of the role and applicability of the wind loading codification used for design purposes. Various factors affecting the magnitude of wind damage to the built environment are identified in a systematic manner, subsequently analysed and their relevance to the proposed risk model is indicated. A database of wind damage and disaster in South Africa is developed and a set of initial observations regarding the trends and characteristics of wind disasters are made.
The proposed model is based on the development of a generic spatial algorithm of wind
damage. Subsequently the wind-related components of the algorithm, relevant to South
Africa, are identified and developed. This is with reference to:

- the identification and definition of the spatial extent of zones of various types of
dominant wind events in South Africa;
- determination of the typical extent (in the horizontal plane) of various types of wind
  events; and
- the development of representative figures on the average rate of occurrence of those
  events per year.

Because of the scope and aim of the current study, the issues related to the spatial
distribution of human amenities as well their wind resistance, is highlighted only and the
relevant data has not been investigated or developed.

The application of the model is demonstrated on the basis of a worked example, based on a
selected administrative district in central South Africa. For this example several arbitrary
assumptions were made regarding the distribution of population and wealth as well as the
wind performance and resistance of various types of amenities.

Finally, an assessment of the proposed model and the relevant reliability considerations are
presented.
Chapter 2
2 WINDSTORM DISASTERS

2.1 International perspective

All natural disasters can have enormous socio-economic impact. Windstorms are regarded as one of the major types of disasters. In fact, the international standard reporting procedures on natural disasters used by the insurance industry (MunichRe), introduces only four categories of natural events namely:

- earthquake,
- windstorm,
- flooding, and
- other (which include: fires, drought, frost, hail, heat-wave and mudslides).

The relevance and impact of windstorm events is demonstrated in Figure 2.1 in which an analysis of the world’s catastrophes for the period 1994-1996 is given (derived from MunichRe 1994-1996). The statistics on the number of events and their consequences are compared. It can be seen that windstorms constitute nearly 30% of catastrophes, cause 20% of deaths and 22% of economic loss. According to Davenport (1995) losses due to wind exceeded those due to earthquakes on an annual global basis.

![Figure 2.1: Comparison of natural disasters](image-url)
An analysis of USA natural disaster events in 1970 and a prediction for the year 2000 presented in Table 2.1 (derived from Petak and Hart, 1979) suggests, that windstorms are responsible for more than 50% of deaths and \( \frac{1}{3} \) of total financial losses due to all natural hazards in the USA.

<table>
<thead>
<tr>
<th>type of loss</th>
<th>% of expected annual losses</th>
<th>year 1970</th>
<th>year 2000</th>
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<tr>
<td>death</td>
<td></td>
<td>47</td>
<td>60</td>
</tr>
<tr>
<td>building damage</td>
<td></td>
<td>27</td>
<td>39</td>
</tr>
<tr>
<td>loss of housing units</td>
<td></td>
<td>60</td>
<td>61</td>
</tr>
<tr>
<td>total loss</td>
<td></td>
<td>33</td>
<td>49</td>
</tr>
</tbody>
</table>

Other statistics (Smith et al, 1995) indicate that up to 90% of total catastrophic losses in the USA between 1986 and 1993 were related to extreme wind events (including hail).

In recent years major wind catastrophes have included events such as:
- 1989 hurricane Hugo which caused $6bn loss in 10 minutes of devastating activity (The Tampa Tribune, 1996),
- 1990 winter storms in Europe in which the insured damage alone, totalled $10bn (Berz, 1991), and
- 1992 hurricane Andrew, destroyed 85 000 houses in Dade county alone, left 157 000 people homeless and total damage estimated at $30 bn. (The Tampa Tribune, 1996).

### 2.2 International Decade for Natural Disaster Reduction (IDNDR)

One of the over-arching goals of the 21st century is to maintain the sustainability of human built development. The crucial importance of this challenge was overwhelmingly supported by the 1990 United Nations General Assembly, and subsequently the Commission on Human Settlements (HABITAT II – Agenda 21).

As one of its major thrusts, the Commission urged governments to promote and facilitate the mitigation of natural disasters. The starting point of such activities should be “the building-up of national collective memories of natural disasters” (Stop Disasters, 1996). This, in turn, would allow the application and optimisation of mitigating activities through the identification
of hazardous land, appropriate materials, designs, building methods and technological assistance.

In all the activities that address natural hazards, a broad trend towards increasing the emphasis on mitigation measures (as opposed to re-construction measures) is evident and this philosophy is enshrined in the goals of the International Decade for Natural Disaster Reduction IDNDR (1990-2000) proclaimed under the auspices of the United Nations.

South Africa has adopted the principles of the IDNDR and these are included in the White Paper on Disaster Management formulated by the Directorate Disaster Management of the Dept. of Constitutional Affairs (1999).

2.3 Wind disasters in South Africa

There are no statistics on windstorm disasters on the African continent. In South Africa there is no formal mechanism for post-disaster technical evaluation and documenting of wind disaster events, although several efforts in that respect have been carried out over the years by the South African Weather Bureau and the CSIR. In the case of large and therefore well-publicised events, socio-economic assessments are carried out by the local and / or national disaster authorities and insurance industry. Until recently, no database of wind damage and disaster existed, despite the fact that several significant devastating events have occurred, with recent examples like:

- Welkom 1990: damage to 4 000 houses, 17 powerlines and R126m economic loss,
- Cape Peninsula, 1997: damage to an estimated 4 500 housing units (both formal and informal),
- Umtata, 1998: 18 people dead and losses estimated at several hundred million rands, and
- Cape Flats, 1999: 5 000 people left homeless and R153m loss.

Contrary to popular belief, the management of the world's biggest re-insurance organisation, MunichRe (Business Day, 2000), suggests that in South Africa the risk of accumulated losses due to thunderstorms, with simultaneous tornadoes and hail, is more critical than the risk of flood. A preliminary investigation undertaken by the CSIR (van Wyk and Goliger, 1995) indicated that typically about five large devastating wind events occur each year in South Africa, and that these events result, among other things, in thousands of people being left homeless.
One of the components of the current project was to develop a database of wind damage events in South Africa and selected statistics which were derived from the database, are presented in Chapter 6.

### 2.4 Disaster planning

Historically, in many countries including South Africa most national and international disaster programmes focussed on immediate rescue activities, followed (where possible) by medium-to long-term recovery programmes. Such efforts, which could broadly be described as relief, will always remain the most necessary aspect of national and governmental intervention.

However, in recent years it has become evident that retro-active disaster alleviation programmes should be supported by a well structured pro-active set of activities which would enable both the introduction of optimal preventive strategies aimed at saving lives and protecting assets before they are lost, and also optimising the application of national resources. One of the vital tools for such preventive programmes are risk models which allow one to determine the likely:

- frequency,
- geographical distribution and extent,
- strength, and
- resultant socio-economic effects

of specific types of devastating events (in a given time domain, i.e. per year).

It is important to note that the risk models allow one to plan and prepare adequate contingency plans, quantify the potential cost of damage before it actually occurs and optimise the pre-allocation of national disaster resources between competing administrative regions.
Chapter 3
3 RESEARCH INTO WIND DISASTERS

Over the last 30 years or so a significant amount of research on wind disasters and the consequent damage to structures has been carried out throughout the world. The underlying aim of this research has been to analyse and gain an understanding of past events in order to minimise and predict the likely devastation and implications of future events.

Research on wind disaster can broadly be grouped into several types of activities which are summarised below. Where relevant, local South African information is highlighted.

3.1 Site investigations and documentation

Most of the significant windstorm events throughout the world were usually followed by post-disaster site inspections and evaluation of the damage, undertaken by local building authorities supported by structural researchers and consultants (e.g. Thompson, 1994; NIST, 1998). In recent years, due to the advancement in understanding of the behaviour of structures under severe wind loads, these visits have become more systematic in their methodology (Sparks et al 1992; McDonald 1995).

Huge events, like hurricane Andrew in 1992 were followed by numerous damage investigations and analyses, research publications, books and even motion pictures (e.g. 'The perfect storm').

In South Africa over the last 20 years or so, the CSIR has been actively involved in wind engineering research which has included numerous windstorm site investigations, some in collaboration with the SA Weather Bureau. These investigations included major disasters like in Welkom in 1990 (CSIR, 1992) or, more recently, in Umtata in 1998 (Mdlekeza et al, 1999) and the Cape Flats 1999 (Goliger and de Coning, 1999).

Figures 3.1a to 3.1r present selected photographs of damage to houses, community and industrial structures, which were obtained during various site investigations. The evidence of damage is arranged in a progressive order (i.e. starting with the least significant damage). Figures 3.2a to 3.2d present samples of the trails and footprints of damage caused by:

- 3 December 1959 storm damage in Prieska, which accompanied a large cyclonic event (Cilliers, 1960),
• 20 March 1990 tornado in Welkom, which was possibly the most devastating wind damage event in South African history (CSIR, 1992),
• 20 April 1994 microburst in Rosendal which severely devastated an informal settlement of several thousand people (Goliger and Adam, 1994), and
• 21 October 1999 a relatively small tornado in Centurion (Goliger et al, 1999).
The footprints of the above events were derived on the basis of comprehensive site investigations and follow-up spatial analysis of the extent of the damage.

The experience of the author, gained during numerous post-disaster site investigations of wind damage, suggests that several factors affect the reliability of the data which can be obtained for further analysis. These are listed below.

• Site inspections should follow the events as soon as possible; with time critical evidence is often removed or modified due to recovery activities and / or theft.

• It is important to collect a set of visual documentation of damage, both general and details of structural failures.

• The report of an event should include weather related information which is relevant for further statistical analysis regarding the type of extreme event.

• Spatial information on the damage is very important and this should be based on a map or aerial photography.

• The investigation should include interviews with reliable eyewitnesses regarding the character of the event, timing and duration, preceding weather, description of the aerodynamic force, etc.
Figure 3.1a: Collapse of a garden wall (Rosettenville, Johannesburg, Oct. 1996)

Figure 3.1b: Overturned information sign; note the presence of bracing (Midrand, Sept. 2001)
Figure 3.1c: Minor damage to the fixing of roof sheeting (Umtata, Dec. 1998)

Figure 3.1d: Minor damage to roof tiling (Midrand, April 1994)
Figure 3.1e: Major damage to roof tiles and glazing; roof trusses and purlins largely intact (Welkom, March 1990)

Figure 3.1f: Entire roof sheeting pulled off and displaced; roof trusses intact (Rosettenville, Johannesburg 23 Oct. 1996)
Figure 3.1g: Portion of the roof totally removed  
(Uitenhage-Port Elizabeth, April 1993)

Figure 3.1h: Total destruction and removal of the roof, walls partially destroyed  
(Midrand, April 1994)
Figure 3.1i: Serious damage to roof and walls (Welkom, March 1990)

Figure 3.1j: Total devastation of the second floor of residential flats (Mannenberg-Cape Flats, Aug. 1999)
Figure 3.1k: Lightweight roof totally removed and collapse of large-span wall (Matsulu, July 1992)

Figure 3.1l: Foundations and toilet units – the only reminder of a lightweight pavilion which was blown away; note that the adjacent structure of similar construction escaped with the loss of the roof only (Piet Retief, Dec. 1986)
Figure 3.1m: Debris from aircraft hangars (Harrismith, Nov. 1998)

Figure 3.1n: Grandstand of a stadium (Piet Retief, Dec. 1986)
Figure 3.10: A telephone pole which has snapped (Heidelberg, Oct. 1999)

Figure 3.1p: Damage to external sheeting of an industrial structure (Centurion, Oct. 1999)
Figure 3.1q: 110 kW power line toppled (Welkom, March 1990)

Figure 3.1r: Several parallel power lines (Welkom, March 1990)
Figure 3.2a: Footprint of windstorm damage in Prieska (3 December 1960)

Figure 3.2b: Footprint of Welkom tornado (20 March 1990)
Figure 3.2c: Footprint of a microburst in Rosendal (20 April 1994)

Figure 3.2d: Tornadic trail of damage in Centurion (21 Oct. 1999)
3.2 Analysis of damage

Analysis of the documented data should be directed at determining:

- the type of the extreme wind event,
- its extent and the likely magnitude of wind speeds,
- extent of damage (per type of structure),
- structural aspects of damage (including engineered vs. non-engineered structures),
- and
- the socio-economic impact of the damage.

The investigation into the type of wind event should be based on general climatic information for the region, combined with weather data pertinent to the event, including the inputs of eye-witnesses and, if possible, the local weather monitoring authority.

The estimation of extreme wind speeds can be carried out directly or indirectly. In some cases, like hurricane Andrew, direct measurements of extreme wind speeds are available (between 60 and 70 m/s - Thompson, 1994). In the case of tornadoes, which usually only affect a very limited area, it is difficult to obtain direct wind speed measurements due to the absence, and in some cases destruction, of measuring devices. In such cases, a determination of wind speeds can be carried out by analysing the documented structural damage. South African examples of extreme wind force evidence (damage) are presented in Figures 3.3a to 3.3j.

One such analysis based on an engineering calculation of the overturning force of a fence (presented in Figure 3.3i), which was flattened by a tornado on 3 November 1993 in Utrecht (Northern Natal), suggested wind speeds in the order of 100 m/s (Goliger, 1994). The site inspection was carried out on the day following the event and the evidence referred to a remote mountain area. Because of this I am fairly confident that the deformation of the fence occurred without being affected by flying debris (both from an impact and wind resistance point of view). Interestingly, further away the same funnel lifted a herd of fourteen fully-grown cattle, carried them about 200 metres and dropped them some 500 metres down a cliff. A similar analysis of temporary fencing at a construction site in Cape Town (Figure 3.3j) indicated wind speeds of about 25 m/s within a built-up environment, close to ground-level.
Figure 3.3a: A steel telephone pole bent but not overturned; note no debris which could have assisted in deformation was found at the site (Heidelberg, Oct. 1999)

Figure 3.3b: Corrugated steel sheeting wrapped around a tree (Welkom, March 1990)
Figure 3.3c: Bent street light (Cape Flats, Aug. 1999)

Figure 3.3d: Bent road-sign (Welkom, March 1990)
Figure 3.3e: A telephone pole twisted at its base (Utrecht, Nov. 1993)

Figure 3.3f: Collapse of two perpendicular sections of a free-standing 220mm brick wall (Umtata, Dec. 1998)
Figure 3.3g: A 4 ton harvester which has been lifted and carried about 500 m (Utrecht, Nov. 1993)

Figure 3.3h: The suspended ceiling of a foyer which was sucked out despite substantial protection offered by a concrete parapet beam connected to the column (Midrand, Sept. 2001)
Figure 3.3i: A wire fence flattened by a tornado (Utrecht, Nov. 1993)

Figure 3.3j: A temporary fence overturned by south-easterly winds (Cape Town, August 1997)
3.2.1 Structural aspects

The analysis of damage to structures often relates to the issue of the conformity of their design and construction to design codes and regulations, which eventually leads to the issue of the adequacy of local guidelines and codification. This issue will be discussed in more detail in Chapter 4. At this stage it is relevant to mention that several analyses carried out in the USA, Australia and UK suggest that wind damage starts to develop at wind speeds far below the design speeds stipulated in the codes, and that compliance with the design and construction standards could greatly reduce the extent of damage due to storms and cyclones.

Thompson (1994) suggests that the weakest components of houses with timber trusses are:
- gable walls and roofs,
- lateral bracing of trusses,
- tying down of trusses, and
- insufficient fixing of roof sheeting.

An insightful set of conclusions regarding typical modes of wind induced damage, depending on the type of buildings, was given by Minor and Mehta (1979). This information, given below in bullet form, was based on the results of an eight-year comprehensive research programme.

- Fully engineered structures often remain unaffected by windstorms and this may give the impression that the storm ‘skipped-over’ them and may lead to false assumptions and conclusions by site investigators.

- In pre-engineered structures (e.g. building systems) failure typically occurs in the cladding and at large openings (e.g. doors).

- Marginally engineered structures (e.g. commercial buildings, light industrial, schools) typically combine brickwork, steel framing and sheeting. Such a combination of materials is often advantageous from an aesthetic and practical point of view, but adequate assembly (i.e. integration) of various components is often lacking.
• Non-engineered structures often provide little lateral resistance to wind and wind speeds of about 120 km/hour (about 30 m/s) typically represent the threshold of damage.

• In buildings the most vulnerable parts are: roof ridges, eaves and corners, corners of the walls, gable walls.

• The increase in positive internal pressure due to the windward openings, combined with external suction can cause damage to a building similar to that of an explosion.

• Weak wall-roof connections can trigger the collapse of large walls.

A remarkable final conclusion is that a small increase in the level of engineering attention may produce large dividends in increased wind resistance.

For masonry walls in India, Somayaji et al (1995) lists the typical places and/or modes of failure as being:

- cantilever elements, parapets and ornaments,
- large glazed openings,
- cracking and collapse of single brick walls (generally near corners or openings), and
- connections between roofs and external walls.

Wiley and Flanagan (1991) undertook a long-term investigation of sites affected by hurricanes, which included ten thousand non-engineered residential and commercial buildings. Both failures, and non-failures of structures were examined and the four main causes of initial failure were identified as:

- inadequate connections (including wood framing, masonry and light steel),
- discontinuous anchorage (from roof to foundation),
- lack of lateral bracing, and
- corrosion of metal fasteners and anchorage (typically in coastal environments).

The authors suggest that the survival rate of non-engineered structures can be improved by introducing clear construction guidelines and their enforcement by knowledgeable inspectors.
3.3 **Statistics of damage to structures**

Statistics on damage are usually given in terms of the number and types of structures and the extent of damage. These largely depend on the geographical extent and severity of the extreme events as well as the type and density of the built environment. For large-scale events like tropical cyclones, damage is often estimated on the basis of the number of houses, and therefore, family units being affected.

For example, hurricane Andrew totally destroyed about 28,000 houses and damaged the roofs of another 135,000 houses; 85,000 of the houses were located in a single county over an area of 400 sq. miles.

A statistical analysis of wind damage in the United Kingdom has been carried out at BRE (Cook, 1984). This analysis considered a ten-year period and included more than five thousand reports of damage. The data was collected from the newspaper clippings and BRE reports. A classification system using type of event (3 types), structure (4 types) and damage (2 types) was applied. Selected statistics indicated that:

- reports referred to events which damaged between one and several hundred buildings, with an average of about 30 buildings,
- damage events indicated strong seasonal and wind directional sensitivity,
- most common damage occurred to roofs,
- brickwork damage was mostly limited to gable walls,
- damage to large structures was largely contained to lightweight cladding and open-sided buildings (e.g. farm buildings, grandstands) - for example over a period of six years 45 grandstands were damaged, and
- several failures were triggered by the effect of dominant openings – (e.g. due to failures of roller-shutter doors or other failures which resulted in an unforeseen dominant opening).

An interesting conclusion was reached by Thompson (1994), who analysed the destruction of houses caused by hurricane Andrew, namely that the resistance of a residential unit increased with the age of the houses in which:

- 31% of houses constructed in the 1970s were declared uninhabitable,
- 39% constructed in 1980s, and
- 59% constructed in 1990s were declared uninhabitable.
3.4 Economic implications

There are numerous analyses of the economic implications of windstorm damage. Most of them were undertaken in the USA and Europe.

The economic analyses relate either to the overall damage to the human environment which is of concern to local and national authorities, or to the financial loss to the insurance industry. These are discussed in the following sections.

3.4.1 National scale

Large windstorms like hurricanes can have devastating economic effects on a national scale. This is particularly applicable to small countries (or islands) in which a single event is able to envelop the entire inhabited area. An example of such situation is the devastation of Jamaica in 1954 by hurricane Gilbert in which the damage exceeded the annual GDP (Davenport, 1995). For large countries with diverse climatic regions (like South Africa), the impact of devastation due to a single event is usually smaller.

In view of the above, the impact of natural disasters on a national scale is usually defined in terms of the damage rate, which refers to the expected annual national damage, divided by the total building wealth (i.e. value of built environment). (Similar rates can be determined for specific climatic or administrative regions.)

Several analyses of the economic aspects of wind disasters in the USA are available. Figure 3.4 presents a comparison of total wind related losses in the USA for the decades of the 1980s and 1990s (INEL, 1997). It can be seen that even if the effects of large events like hurricane Andrew are ignored, a clear trend of increasing losses with time is evident.

Petak and Hart (1979) determine a damage rate (defined as a percentage of total value of built environment) of 0.28% for all natural disasters. About 27% of this is wind-related. A prediction for the year 2000 suggests this percentage will increase to 39% (see Table 2.1).
Friedman (1979) identifies four categories of damaging windstorm events namely:

- hurricanes,
- winter storms,
- tornadoes, and
- thunderstorms (including downbursts),

and suggests that the total loss due to catastrophic events is more or less twice that due to non-catastrophic events.

Friedman also reports that two independent analyses of catastrophic events, one of which included more than 400 events with damage larger than $1.5m in 1978 monetary terms, suggest that:

- about 40% to 50% of the events are hurricanes,
- about 40% to 45% tornadoes and thunderstorms, and
- the remainder are winter storms.

No similar information for South Africa is available, apart from the assessment, in terms of the cost of damage, of selected individual events.
3.4.2 Relative scale

From a disaster management point of view, the critical aspect of a potential devastating event is its likely spatial scale (extent) in relation to the extent (size) of the human built development under consideration.

For example, from a national perspective an occurrence of a devastating thunderstorm affecting localised communities would probably be treated as of relatively little concern (almost a statistical issue to be expected within a season of convective activity, for which contingency plans should be in place) as opposed to other types of disasters like, for example, a prolonged drought affecting large geographical regions. A devastating thunderstorm could be of more concern to the provincial authorities and of significant concern to local authorities. For local communities, although the probability of occurrence of a devastating event is small, the potential consequences are of great concern.

In South Africa, due to large disparities in the wealth of various communities, this issue may also have another dimension. For example in a case of a poor or developing and densely populated administrative region (e.g. KwaZulu Natal or the Northern Province), even an event of relatively low severity, but that envelopes the entire region, can have devastating consequences on the livelihood of entire communities. In contrast, a severe wind event, in a densely developed suburb of Johannesburg may cause a significant financial loss (which would probably be covered by insurance) but may inflict very little or no human loss or tragedy in terms of economic consequences.

3.4.3 Insurance industry

In any catastrophic event, insured property forms only a part of the overall damage. Nevertheless the impact of large windstorm disasters on the insurance industry is enormous. Following the 1970 hurricane Celia, no insurance cover became available along the Texas coastal areas (Wiley and Flanagan, 1991); hurricane Andrew led to the bankruptcy of 30% of insurance companies in the USA and had a serious effect on Britain's Lloyds (INEL, 1997).

It is estimated that along the Atlantic coast of the USA, Canada and Gulf of Mexico, about $13.5 trillions worth of insured property is at risk due to hurricanes. Furthermore, the policies cover only about 50% of what should be covered (INEL, 1997). The remaining loss usually becomes a burden on the national coffers, in the form of direct financial support and various other forms of assistance (e.g. long term or interest free loans etc).
According to Friedman (1979) about 65-70% of wind damage in the USA is typically covered by insurance. In developing countries this percentage is substantially lower.

Wiley and Flanagan (1991) suggest that as a result of several devastating windstorm events, the insurance industry stipulated mandatory code compliance as a prerequisite for insurance cover in certain parts of the USA.

3.4.3.1 Insurance cover

Upon receiving a request for insurance cover, the cover provider attempts to assess the probability (i.e. the risk) of a loss. This includes meteorological information on the geographic distribution, probabilities of extreme wind velocities and also engineering information on the wind damage vulnerability of the particular structure.

Alternatively, historical information on damage to similar structures is re-visited. This analysis allows the provider to establish the magnitude of a probable claim, over a period of time, and then to determine an appropriate premium. The financial analysis of historical data is often difficult due to the simultaneous occurrence of various damaging factors (insurance perils) (e.g. wind, hail, rain and lightning).

Because these difficulties, the insurance industry has tended to group various types of hazards (e.g. explosion, fire, flood and wind) into a single package (e.g. homeowner policy). The buildings are typically categorised on the basis of their usage, and the quality of their engineering design and construction is often ignored.

On the other hand, as a result of market competitiveness and constant pursuit for sophistication, a new trend is evident in some countries to separate and define windstorm hazards based on categorisation of buildings in terms of their susceptibility to damage (Mehta et al, 1991).

Berz (1991) suggests a few important measures to improve the cover (decrease the risks) of the insurance industry as given below:

- larger participation by the policy holders,
- limited liability for excessive exposure,
- more accurate descriptions of geographical risk zones,
- reduction in the number of low-cost claims, which typically constitute most of the total settlement amount.
In South Africa the records of damage claims of various insurance companies are kept for a period of three years only making it impossible to research the history of financial loss. Furthermore, no individual records of payouts regarding the various types of events are kept by the insurers, making it impossible to develop any overall figures on a national scale. However, the damage due to storms is considered as one of the critical factors affecting the profits of the insurance industry (Business Day, 2000).

### 3.4.3.2 Vulnerability function

The relationship between wind speed and the consequent damage is typically referred to as the vulnerability function. The insurance industry uses vulnerability curves for actuarial calculations of the overall insurance exposure loss for a region. Those analyses often do not go beyond the development of generic vulnerability curves for a combined portfolio that includes various types of structures.

Figure 3.5a shows an idealised vulnerability curve for a fully-engineered building (Holmes, 1996). In this figure, damage index refers to the ratio of repair costs and the initial building cost. In Figures 3.5b and 3.5c vulnerability curves of commercial buildings in the USA and Puerto Rico are presented (Khanduri and Morrow, 1999). Note that no division or description of the axis is given for business confidentiality purposes. Interestingly, irrespective of the type of construction method, the vulnerability curves seem to indicate a similar threshold wind speed for the initial damage. (Presumably all the structures which were considered were assumed to be formal. Such a situation is clearly not applicable to the South African built environment, which also consists of a large informal settlement sector.)
Berz and Smolka (1988) mention that a threshold wind speed of damage of Beaufort 8 (corresponding to ca. 16 – 20 m/s, mean wind speed) is specified by most insurance companies as a prerequisite for insurance protection. It is not clear if this also applies to South Africa.

The vulnerability curves obtained from an analysis of the damage due to winter storms in Europe is presented in Figure 3.5d (Drayton et. al 1999). The differences in building types, technologies and practices across western European countries contributed to the scatter of the data.
3.5 Prediction of damage and risk models

One of the loss mitigating tools that is desirable for both the insurance industry and disaster management authorities, is the assessment or prediction of potential future damage.

The prediction of the magnitude of individual disastrous events and their consequences would form the most useful information from both the national and reinsurance points of view. For example, in the five year period between 1989 and 1994, thousands of lives were lost in the USA due to severe windstorms and seven of the most costly disasters totalled $85 billion (of which 40% came from the national treasury). A scenario of one major future event impacting on Miami indicates a loss of $75 billion (INEL, 1997).

Information on the risk of damage due to a specific type of event is fundamental to disaster management activities because it allows integration of the probability of the extreme event occurring with the consequences of such an event. In a nutshell a wind damage risk model should identify:

- the probability of occurrence of extreme events per unit area (i.e. administrative region or kilometre square) and in terms of their intensities,
- the vulnerability of the built environment (i.e. exposure of population and type of structures),
- potential consequence per time unit (e.g. year), and
- extension of probability and magnitude of consequence, which constitutes a higher level of application necessary for disaster planning.
The risk analysis should be carried out on the basis of the history of events and their consequences and its outcome should be a probabilistically-based model of annual mean rate of occurrence in geographical terms. Several risk models have been developed, typically to determine the probability of tornadic strikes and wind speeds (e.g. McDonald (1983), Twisdale (1988), Milford and Goliger (1995) and Cassaro and Chiu (1999)). (Two of the above models are based on the principle of a generic footprint of a tornadic event.)

In Figure 3.6 a map of the mean rate of occurrence of tornadoes in South Africa is presented (Goliger et al, 1997). This map has been developed on the basis of confirmed events using a geo-statistical spatial analysis developed by Journel and Huijbregts (1978).

Following the devastating winter storms of 1987 and 1990 in Europe, the development of a risk model of loss was reported by Drayton et al (1999). In order to determine the geographical risks, a comprehensive analysis of 2 300 historical storm tracks was carried out. This led to the development of a footprint of a generic stochastic extra-tropical storm (i.e. low pressure frontal cyclone) as presented in Figure 3.7. (Although not indicated in the paper, it can be inferred that the wind speeds refer to observed peak gusts. No indication is given as to the elevation to which these wind speeds refer.) The extent of the footprint determines the size of the areas subjected to various ranges of wind speeds. (This has been calibrated against long-term statistics of extreme wind speeds in the UK and France.)

A comprehensive risk model of the potential cyclonic damage along Australia's northern coast has been developed by Leicester et al, (1979). This model was based on the probability of a 3-sec gust wind speed occurring (i.e. regional design wind speed) measured at several major population centres. The authors stress, however, that the regional design wind speed is used solely as a reference, and does not imply that wind damage is caused by a peak gust only.
Figure 3.6: Mean rate of occurrence of tornadoes in South Africa

Figure 3.7: Generic footprint of a European winter storm (note the contours of the UK, France etc.)
3.5.1 Scenarios of damage

The determination of the consequences of a potential single catastrophic event is particularly important for the national authorities and insurance industry. This can be derived from historical data of extreme events, the identification of the most critical type of event and developing a scenario for such an event. Such a model should consider the changes in the influencing factors in time domain e.g.:

- the climatic patterns, affecting the probability of a strike of a damaging event,
- geographical distribution of assets,
- damage susceptibility (i.e. changes in design and construction methods), and
- the cost of repairs.

Another way of developing such a scenario is to superimpose the information of extreme wind speeds on the geographical distribution of human built development (i.e. property at risk). Huang et al (1999) developed a simulation of hurricane damage based on the 50-year return period wind speeds and historical insurance loss data to obtain the expected annual loss.

Further refinements can also take into account the composition and structural aspects of the built environment (i.e. the vulnerability of different types of construction).

A hypothetical scenario of damage due to a worst-case tornado event in South Africa has been prepared by the author of the current dissertation (Goliger, 1996) at the request of a large insurance organisation. This was developed using a GIS system combined with statistics on the characteristics of South African tornadoes, and financial data from the 1990 Welkom tornado. It was estimated that about 1 500 buildings would be totally destroyed and a further 4 500 affected substantially. The total cost of damage to houses was estimated to be about R250m in 1996 rand plus damage to other structures and a substantial loss of sales to ESKOM.

3.5.2 Categorising the structures

A logical way to handle the issue of prediction of potential damage is to categorise structures in terms of their vulnerability to extreme winds. Several such systems have been developed in order to support the prediction models of potential damage.
In the model developed by Leicester et al (1979) for Australian conditions, the potential damage to houses is defined in terms of a damage index, ranging from 0 to 1, as presented in Table 3.1a. The factors affecting the strength of buildings are identified (Table 3.1b) and building strength is divided into 5 categories in terms of threshold levels of gust wind speed capable of inflicting minor and major damage (Table 3.1c). This was followed by a survey and categorisation of houses in terms of terrain type and building strength. The integration of the data with the probabilities of wind speed occurrence allowed the determination of expected damage in relation to regional gust velocity.

Table 3.1a: Definition of damage index for a house

<table>
<thead>
<tr>
<th>worst damage feature</th>
<th>damage index*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>elevated</td>
</tr>
<tr>
<td></td>
<td>low-set</td>
</tr>
<tr>
<td></td>
<td>brick walls</td>
</tr>
<tr>
<td></td>
<td>asbestos</td>
</tr>
<tr>
<td></td>
<td>cement walls</td>
</tr>
<tr>
<td>negligible</td>
<td>0.00</td>
</tr>
<tr>
<td>missile damage to cladding or windows</td>
<td>0.05</td>
</tr>
<tr>
<td>loss of half roof sheeting</td>
<td>0.10</td>
</tr>
<tr>
<td>loss of all roof sheeting</td>
<td>0.20</td>
</tr>
<tr>
<td>loss of roof structure</td>
<td>0.25</td>
</tr>
<tr>
<td>loss of half of walls</td>
<td>0.50</td>
</tr>
<tr>
<td>loss of all walls</td>
<td>0.75</td>
</tr>
<tr>
<td>loss of half of floor</td>
<td>0.85</td>
</tr>
<tr>
<td>loss of all floor</td>
<td>0.95</td>
</tr>
<tr>
<td>collapse of floor support piers</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*damage index = (repair cost/initial cost of building)
Table 3.1b: Factors affecting the strength of houses

<table>
<thead>
<tr>
<th>Aspect</th>
<th>feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>design</td>
<td>1. wind sensitivity of the structure</td>
</tr>
<tr>
<td></td>
<td>2. quality of engineering design, if any</td>
</tr>
<tr>
<td></td>
<td>3. reliability of the application of current engineering theory to the</td>
</tr>
<tr>
<td></td>
<td>particular house structure</td>
</tr>
<tr>
<td>approval</td>
<td>1. structural engineering ability of the approval authority</td>
</tr>
<tr>
<td></td>
<td>2. degree to which critical aspects of the structure are shown on the</td>
</tr>
<tr>
<td></td>
<td>plans</td>
</tr>
<tr>
<td>supervision</td>
<td>1. the understanding of structural engineering principles by the field</td>
</tr>
<tr>
<td></td>
<td>inspector</td>
</tr>
<tr>
<td></td>
<td>2. the number and variety of structures supervised within a given</td>
</tr>
<tr>
<td></td>
<td>period</td>
</tr>
<tr>
<td></td>
<td>3. the type of structure with respect to the effects of possible errors</td>
</tr>
<tr>
<td></td>
<td>in supervision</td>
</tr>
<tr>
<td>construction</td>
<td>1. the quality of workmanship associated with the construction of</td>
</tr>
<tr>
<td></td>
<td>critical structural features</td>
</tr>
<tr>
<td></td>
<td>2. the quality of the structural materials</td>
</tr>
</tbody>
</table>

Table 3.1c: Classification of basic house structures

<table>
<thead>
<tr>
<th>house structure type</th>
<th>wind gust velocity (ms⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>minor damage</td>
</tr>
<tr>
<td>A</td>
<td>35</td>
</tr>
<tr>
<td>B</td>
<td>40</td>
</tr>
<tr>
<td>C</td>
<td>45</td>
</tr>
<tr>
<td>D</td>
<td>50</td>
</tr>
<tr>
<td>E</td>
<td>∞</td>
</tr>
</tbody>
</table>

A knowledge based system of wind resistance categorisation has been developed by Smith et al. (1995). (Sandri and Mehta (1995) extended this idea further and proposed the use of a neural network theory.) In the system proposed by Smith et al., the structures are indexed in a relative grade, which is a measure of the susceptibility to damage compared with other buildings of similar structural parameters. Eight building categories were identified as:

- high-rise (more than 6 storeys)
- reinforced concrete
- heavy steel
- reinforced masonry
- light steel
- timber
- masonry, and
- non-engineered.

The relative grades assigned to each category reflected the degree of engineering attention as shown in Figure 3.8a, where Grade 1 corresponds to least susceptibility. The buildings are then assessed in terms of five groups of parameters as presented in Figure 3.8b.

Figure 3.8a: Range of relative grades for different building categories
### 3.6 Construction guidelines

One of the most relevant and pro-active ways of reducing the potential for wind devastation is to research the historical damage data, identify the good and bad local construction practices and to promote the optimal structural solutions and details. According to Prof Davenport (1995) the development of the link between a substantial pool of existing scientific knowledge and construction practice is one of the remaining great challenges of wind engineering.

A substantial amount of work on the development of wind-related construction guidelines has been carried out in several countries (e.g. the USA, Australia, India, Pacific Rim) but not in South Africa. A brief review of the relevant literature and an assessment of its applicability to South Africa, is included in the current section.

Saffir (1971) suggests that before the actual specifications and guidelines regarding the structural wind resistance aspects of a proposed structure are drawn, the architect or designer should ask himself (herself):

- Will the structure be inspected by competent engineering personnel?
- Will the structure be ever used as public shelter?
- Can a localised failure lead to progressive collapse?
- Can failure of the structure trigger failures of adjacent structures?
Damage surveys conducted by Texas Tech University between 1970 and 1975 (Minor, 1982) revealed that the built environment in the USA does not offer adequate protection for people against the severe storms and tornadoes. Furthermore, a fairly consistent pattern was identified in which even in the most severe cases of residential damage, small interior compartments (bathrooms or closets) escaped relatively unscathed. This has resulted in research and development of architectural and construction guidelines on creating protective areas and strong rooms rather than tornado-shelters for residential housing. For public areas and schools, dedicated shelters are stipulated (Melaragno, 1982 and Minor, 1982) and Bilello (1999) proposes an architectural design of tornado shelters for mobile homes and schools.

Figures 3.1c to 3.1g present typical failures of roofs in South Africa. The most frequent mechanism of failure is the uplift of roof sheeting as presented in Figures 3.1c and 3.1f. Somayaji et al (1995) stipulate a set of considerations that aim to increase the wind resistance of sheeted roofs. These include:

- adequate size and type of bolts,
- arrangement, position and number of bolts depending on the location of the sheet within the roof,
- effective washers,
- cyclonic ties (connecting trusses and walls), and
- adequate punching, shear and bending capacities of the sheets.

Golden and Snow (1991) suggest a typical sequence of failure of residential structures in which:

- the windows or doors fail and allow internal pressure to build up,
- the internal pressure (positive) combined with negative pressures on the roof causes uplift of the roof, and
- subsequent collapse of one or more walls.

Furthermore, they refer to the damage to masonry buildings as typically being caused by violation of height / thickness ratios, the absence of reinforcement and anchorage of roof.

In the case of entire roofs (or portions thereof), the optimal mitigation measure to prevent uplift, is adequate anchorage to walls and where lightweight walling systems are used, the anchorage of walls to foundations.
For the traditional brick house in South Africa, adequate anchorage of roofs to walls is sufficient. However, as a result of the constant pursuit of more economical design and construction combined with a trend for a new generation of lightweight building structures, the issue of the anchorage to the foundation (or ground) becomes increasingly relevant (Figure 3.11). (The same applies to the informal shelters which often use metal (or other) lightweight sheeting for wall construction as presented in Figure 3.9.)

For structures of brick and block, it is important to provide ring-beams (tie-beams) around the perimeter of each floor to accommodate the uplift ties and to provide rigidity in the lateral direction (Saffir, 1971).

![Figure 3.9: Typical informal shelter assembled from metal sheeting](image)

In the opinion of the author, the presence of a ring-beam can considerably reduce the risk of uplift of the entire roof structure. In many cases of failure observed in South Africa the roof ties were present; however, the resistance (and mass) of the brickwork proved to be insufficient as is shown in Figures 3.10a to 3.10c.
Figure 3.10a: Failure of roof and damage to walls caused by inadequate roof ties (Piet Retief, December 1986)

Figure 3.10b: Failure of roof and damage to gable wall caused by inadequate roof ties (Cape Flats, August 1999)
McDonald (1995) raises the issue of the compliance tests for roof systems used in practice, which are of a static nature and, therefore, do not simulate the true dynamic effects of wind loading. This issue is of great relevance to South African conditions and construction practices and should be addressed by the introduction of a dynamic magnification factor to be applied to the static loads.

According to Golden and Snow (1991) in nearly 50% of cases the weakest part of residential buildings are the garage doors and their failure triggers damage to roofs and walls. This has been echoed by Cook (1984) who refers to UK surveys in which failures due to the effect of a dominant opening is commonly caused by the unintended failure of roller-shutter doors.

The above is broadly confirmed by the experience gained during inspections of wind devastation sites in South Africa carried out by the author, in which the garages often constituted the most devastated parts of buildings. An example of this is presented in Figure 3.11. Another typical cause of damage in South Africa is the collapse of large sections of unsupported walls as presented in Figures 3.12a and 3.12b. (This issue will be discussed in more detail in Section 5.5.3.6.)
Figure 3.11: Devastation of a garage (Welkom, March 1990)

Figure 3.12a: Collapse of unsupported walls in formal housing (Matsulu, July 1992)
Sherman (1973) analysed the additional structural requirements (e.g. fasteners, bracing, sizes of elements) necessary for tornado-resistant houses. He estimated the cost increase due to these additions to be about 20% of the initial cost of the structure.

Eaton (1979) proposes a permanently open roof ridge ventilator, which would reduce forces by equalizing the internal and external pressures. Gandemer and Moreau (1999) extend the idea of ridge pressure equalization further and propose a central-shaft concept based on a pressure balancing principle. Comparative wind-tunnel tests for one specific geometry of a house, indicate a drastic change in the distribution of pressures, in most cases converting the negative (outwards forces) to positive.

3.7 Reconstruction and repair

Depending on the degree of devastation, the affected structures could either be refurbished or rebuilt. In the case of total destruction like that presented in Figures 3.1i to 3.1k the structure would largely have to be rebuilt from the foundation level up. (In some cases in which the structural elements (e.g. columns) are connected to the base, reconstruction of foundations is also necessary.) Minor damage to property like loss of roof sheeting, glazing or collapse of garden walls can be reinstated promptly and at fairly low cost. The uplift of an
entire roof or a portion of it usually also includes structural damage to the upper sections of the walls.

The damage to large (e.g. multi-storey) engineered structures is usually limited to the glazing or sheeting. In severe winds structural damage may also occur. Structural repair work to a multi-storey building has been reported by Mehta et al (1971).

Finally, the issue of preparedness guidelines is also relevant. These may not necessarily be aimed at increasing the wind resistance of structures, but may significantly reduce loss of human life and also to some extent material loss due to specific events. An example of such a guideline is that issued by the US Department of Commerce (1992).

3.8 Policies

All natural disasters including windstorms have a tremendous socio-economic impact as a result of loss of human life and injury as well as damage to property. These effects are often prolonged as in many cases the communities and authorities do not have sufficient resources and systems in place to carry out adequate post-disaster recovery activities.

Consequently there is a broad tendency across the field of managing natural hazards to emphasise mitigating measures rather than rely on relief and reconstruction in the wake of disasters. An important initiative of the United Nations in 1990 aimed to reduce the loss of life and property as a result of natural disasters. Specific targets have been proposed for each type of hazard for the 1990-2000 IDNDR Decade (Davenport, 1995) including, among other things, evaluation of:

- the geographical distribution of threat (in the form of maps),
- recurrence intervals and impacts,
- vulnerability of the most important concentrations of population and resources,
- optimal land use to avoid hazards,
- construction practices to resist the impact (quality standards and processes inclusive of all role players in the industry), and
- awareness programmes and training.

Over the years systems to collect information have been developed and detailed studies of extreme wind events undertaken mainly in the USA, Europe and Australia. In early 70s efforts had already been directed at identifying potential impacts, mitigation technologies and
policies of windstorm disasters, including land use planning (Petak and Hart, 1979; White, 1979).

These proactive policies combined with adequate funding, resulted in a significant amount of research being undertaken in places such as:

- Natural Hazard Research and Applications Information Centre, University of Colorado,
- Institute for Disaster Research, Texas-Tech University,
- BRE's Overseas Division, Garston,
- Centre for Building Technology, US National Bureau of Standards,
- National Oceanic and Atmospheric Administration (NOAA), US Dept. of Commerce,
- Cyclone Testing Station, James Cook University, Queensland, and
- Faculty of Science, University of Buenos Aires.

A comprehensive list of the research centres in the USA is included in McDonald (1995).

Ironically major windstorm disasters often affect the poorest countries and communities of the world. The author's belief is that this could largely be attributed to three factors namely:

- the geographical distribution of climatic zones of extreme winds coinciding, to a large extent, with the distribution of underdeveloped countries of the world,
- the large population densities (typically at low and coastal areas and within large urban centres), and
- insufficient financial resources in poor countries leading to a lack of adequate materials, technology and erection methods within the construction industry.

According to Cohen (1999) effective wind hazard reduction measures at a national scale include:

- education of the general and engineering public regarding windstorm phenomena and their consequences, including access to relevant information,
- forecasting (i.e. development and implementation of long- and short-term refined prediction systems),
- effective construction practices (i.e. development of technologically and economically viable design and construction methods),
- data collection and retrieval including: meteorological data, inter-disciplinary damage assessment and development of relevant databases,
• development and introduction of appropriate, reliability based, codes and standards that include windborne missile specifications, and
• the introduction of sufficient emergency management (i.e. organisation of services and disaster relief).

Some practical suggestions proposed by Davenport (1995) include:

• increase awareness of investors and owners concerning construction quality, long-term life cycle vs. initial costing,
• provide incentives for hazard resistant construction through reduced premiums; use proven engineering procedures to verify quality,
• legislate the responsibility for construction standards of public buildings, and
• develop user-friendly codes and guides.

Finally policies regarding the design of structures are of critical importance. Where the consequences of damage or failure are potentially catastrophic (e.g. nuclear industry, petrochemical and communication facilities) much stricter design specifications should be applied than in respect to the built environment in general (Minor, 1982).
Chapter 4
4 CODIFICATION OF WIND LOADING FOR STRUCTURAL DESIGN

4.1 Role and applicability of wind loading codes

Wind constitutes one of the most critical environmental loadings on structures. From a design point of view, an optimal, if not the only, way to minimise the wind induced damage to structures is to enforce a set of scientifically proven and probabilistically based, technical rules and regulations to be adhered to in the design process. This statement implies a direct relationship between the issues of codification of wind loading and wind damage and disaster reduction.

In the USA, a follow-up of many large-scale windstorm devastations focused the attention, and potential criticism, of all role players (i.e. affected communities, authorities, designers, builders, professional bodies and media) on the inadequacy and poor implementation of the design codes and building regulations (ENR, 1986, 1989, 1992 and 1994). Furthermore, critics claim that in recent years the development of progressive design procedures have not kept pace with the dramatic improvement in the understanding of the effects of wind on buildings.

Greenwood and Hatheway (1996) indicate that an analysis of the damage caused by Hurricane Opal suggests fewer than 1% of structures conforming with structural standards were damaged. Such a statement implies that it is possible to design structures to withstand violent storms like hurricanes. Golden and Snow (1991) suggest that concrete and reinforced masonry construction, designed in accordance with the building codes and specifications, perform remarkably well under cyclonic wind conditions.

In his conclusion of a survey of UK wind damage events, Cook (1984) suggests that the actual damage starts at wind speeds far below the design speeds stipulated in the code. Furthermore, the preliminary results of a survey undertaken by the Loss Prevention Council suggests that as many as half of all roofs of residential housing will fail at no more than half the design wind speed (LPC, 2000).

A similar sentiment has been expressed by Thompson (1994), who analysed the destruction of houses in the USA by hurricane Andrew. He suggests that the main reason for this situation is the general lowering of construction standards, relaxations and violations of codes, and construction errors. These are the results of the constant pursuit for cheaper
design and construction methods to satisfy the need for affordable houses. A similar conclusion has been reached by McDonald (1995).

Walker et al (1987) claim that strict compliance with modern regulations and design codes in Australia has ensured that practically no damage to recent structures subjected to cyclonic conditions has been observed. Sparks et al (1992) mention that some carefully designed wood-framed houses at exposed locations experienced gusts in the excess of 60 m/s (during the 1989 hurricane Hugo) without sustaining any damage.

4.2 Principles and international perspective

As with any loading that is considered when designing a structure, structural element or foundation, wind load is a statistical quantity. In particular, its variation with respect to time and space is pronounced. To cater for these properties, loading codes throughout the world developed individual systems of determining the nominal wind loads (which were subsequently combined with partial load factors and load combination factors).

In order to define the magnitude of the nominal loads, design codes have developed sets of consistent information on:

- the extreme winds (i.e. free-stream pressures) including their: geographical distribution, characteristics, magnitude (in statistical terms), air densities, and in some cases even the directional characteristics,
- the influence of localised features like: terrain roughness (i.e. wind profile), topography and shielding, and
- the susceptibility of various types of structures to wind flow, in other words the capacity to generate certain magnitudes of wind pressures and forces while subjected to wind flow.

In the early 1950s, several of the national codes of practice which were introduced throughout the world were based on the old Swiss building code (reference unknown). The information on pressure coefficients referred to the mean value and was based on early measurements which were carried out in mechanical (i.e. laminar flow) wind-tunnels. The nominal forces were defined in combination with the gust wind speed estimated to be exceeded once in 50 years.
Over the years more data has been obtained from measurements in simulated boundary layers and has been introduced into various codes. In the past 15-20 years a philosophy of adopting the mean wind speed has emerged due to its relevance and applicability to the dynamic design of structures. Codes which implemented this philosophy (BS 6399 and ENV 1991-2-4) then reverted to hidden conversions to peak wind speeds for purposes of compatibility with the data on pressure coefficients.

4.3 South African wind loading specifications

The current South African loading code (SABS 0160-1989) was developed between 1970 and 1985. Its wind loading stipulations are based on the British Code (CP3 1952) modified to satisfy South African conditions by Milford (1987). The code is based on the principle of a 3-sec gust wind speed with a 1 in 50 year return period.

A committee was set up in 1999 under the auspices of the South African Bureau of Standards and the loading specifications of the code are currently being revised, including wind loading. The results of comparative research into the wind loading stipulations and a proposed way forward are presented in Goliger et al (1998) and Goliger et al (2001).

It was established that there would be merit in following the principles included in two modern codes (i.e. Australian and ASCE (USA); in particular the overall logic of the Australian code combined with its comprehensive information on pressure coefficients, and the simplicity of certain procedures included in the ASCE code make this option attractive. The main principles of the wind loading revisions which are proposed, are as follows.

- In view of the conflicting trends and discrepancies which are evident when different modern codes of practice are compared, a route of simplicity and continuity with the current SABS 0160 version is proposed (where possible).

- The fact that a large portion of wind damage in South Africa occurs to non-structural, often informal amenities which do not receive any design inputs, makes this approach even more relevant as such a situation does not warrant the sophisticated calculation models applied to certain facilities only.

- Following the logic of the Australian code by dividing design methods into three categories: Simplified, Detailed Static and Dynamic.
(For the vast majority of structures in South Africa, the resonant dynamic effects are small and can be ignored and, therefore, the proposed approach provides simplicity and allows the designer of most structures to ignore the dynamic issues.)

- Maintaining the principle of the design peak wind speed and four terrain categories in combination with a simple power-law profile, similar to that used in the ASCE (1996) code (i.e. without the zero-plane displacement).

- Discontinuing the principle of classes of structures (e.g. 3, 5 and 10-sec profiles) and replacing it with a procedure on correlation of pressures.

- Maintaining the principle of two different maps of design wind speeds (3-sec gust and hourly mean) and replacing the mean return period with an importance factor.

- Stipulating a simplified procedure to account for changes in terrain category, but to adopt a detailed procedure on the influence of the dominant topography.

4.4 The relevance of wind codification to South African conditions

Finally, the issue of the broad relevance and adequacy of the wind loading stipulations of the national design code (SABS 0160) to South African conditions must be raised.

Current codification considers structures and building structures and tends to marginalise other amenities not covered by building regulations but still susceptible to wind damage. However, it provides a useful basis for determining acceptable levels of damage and this principle needs to be extended to cover other non-structural amenities.

As discussed in Chapter 3 (and also raised in Chapter 5), the vast majority of damage in South Africa is triggered (and often limited) to essentially non-structural elements or amenities (e.g. garden walls, small cladding, sheeting elements, awnings etc.). Meanwhile, and for structural safety reasons, most of the emphasis in the code is placed on the design of load-bearing structures, roofs and building elevations.

Furthermore, a large portion of the wind damage in South Africa occurs to buildings and structures which have had very little or no engineering inputs before or during their
construction. An example of such a development would be the informal human settlements, which, in fact, house a significant portion of the South African population.

The above situation can be perceived as a deficiency in the wind loading codes and forms one of the gray areas within the design and development chain, which can only be addressed by a partnership between the design professionals, local and disaster management authorities.

The proposed model provides a tool for assessing the magnitude of the expected cost of damage in South Africa and can therefore motivate the extension of the national codes to include non-structural issues, amenities and elements.
Chapter 5
5 FACTORS THAT INFLUENCE WIND DAMAGE

There are several factors that influence the susceptibility of the built environment to wind and consequential loss and damage. The best examples that support this statement are the two hurricane events of 1978 which both affected developing countries - Sri Lanka and Belize. One left millions of people homeless and thousands dead in Sri Lanka (with an area of 66 000 km sq. and population of nearly 14 m), whereas the other (in Belize with a population of 150 000 and an area of 23 000 km sq.) damaged only few hundred houses and killed five people (Eaton, 1979).

The influencing factors can broadly be grouped into: climatic (i.e. the severity and geographical extent of extreme wind events) and human / developmental (population density, vulnerability of structures etc.). It is not a coincidence that several of the factors relate directly to stipulations of wind loading design codification. An overview of the relevant factors is given below and a follow-up discussion is included in Chapter 7 in which the framework of the proposed model for South Africa is presented.

5.1 Classification of severe storms

The scale and severity of extreme wind events is one of the most significant factors influencing the consequential damage and a basic knowledge of the types and characteristics of local windstorms is therefore essential for developing wind damage models for a specific geographic region.

Most high winds are associated with frontal cyclones, tropical cyclones and thunderstorms. Other types of strong winds (like the mountain down-slope winds (i.e. berg winds)) are caused by topographical and thermal effects rather than severe storms. A brief description of various types of windstorm follows.

*Frontal cyclones* (Eagelman, 1983) are the largest travelling atmospheric vortices, with diameters typically between 1000 and 2000 km. These low-pressure storms occur in the middle and high latitudes (i.e. greater than 30 deg) in both hemispheres, during the cooler months of the year in the northern hemisphere and throughout the year in the southern hemisphere. Frontal cyclones travel at speeds between 15 and 50 km/hour and the associated surface winds may reach 100 km/hour (27 m/s). Frontal cyclones typically last few days and can occasionally produce pre-frontal squall-lines.
Tropical cyclones occur in many parts of the world and are often referred as to typhoons (east Asia), hurricanes (North America) and cyclones (Indian Ocean). They are generated over oceans with a surface temperature greater than 27 deg., between latitudes 5 and 30 degrees. Their average diameter is about 500 km and typical surface wind speeds are up to 45 m/s (160 km/hour) although much higher speeds have been reported (Golden and Snow, 1991). Tropical cyclones usually dissipate as they move inland, but they can also transform into frontal cyclones and can produce a large number of thunderstorms and tornadoes. (Interestingly, Golden and Snow (1991) mention that one hurricane produced 115 tornadoes along coastal Texas.) The intensity of hurricanes is usually rated according to the Saffir-Simpson Scale.

Thunderstorms develop as a result of significant upward movement of air caused by the thermodynamic convection process in which rising hot air cools, saturates and forms a cumulus cloud. The cell can develop into three typical arrangements namely: isolated thunderstorms, squall lines and a large complex supercell.

Supercell thunderstorms can give rise to several downbursts and tornadoes. Downbursts are generated by a falling mass of cooled air which falls to the ground and spreads out horizontally so generating extreme winds of short duration.

Downbursts are classified into two groups (Fujita, 1981): macrobursts with an affected area of 1 to 5 km and duration 5 to 30 minutes and microbursts with an area of few hundred metres and a duration 2 to 5 minutes.

Tornadoes are typically associated with very hot air masses and severe thunderstorms although cold front tornadoes also occur in Europe and America. Despite several years of research, the formation of tornadoes is not fully understood. In the northern hemisphere tornadoes almost always rotate counter-clockwise and in the southern hemisphere clockwise. The intensity of tornadoes is usually classified in terms of the Fujita / Pearson classification as presented in Table 5.1 (Fujita, 1973).

Mountain downslope (berg) winds happen when a cold layer of air descends from a mountain peak as presented schematically in Figure 5.1 (Liu, 1991). Due to acceleration caused by gravity, at the foothill the wind can reach wind speeds as high as those of hurricanes. These winds are typically generated by cold fronts.
In summary it can be seen that there are major differences between various types of strong and severe wind events but the most important ones which will affect the proposed risk model, are the differences in spatial extent and the wind speeds that are generated.

Table 5.1: Fujita / Pearson Tornado Scale (after Fujita [1973])

<table>
<thead>
<tr>
<th>maximum wind speed (m/s)</th>
<th>path length (km)</th>
<th>path width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0 20 - 30</td>
<td>P0 0.5 - 1.5</td>
<td>P0 5 - 15</td>
</tr>
<tr>
<td>F1 30 - 50</td>
<td>P1 1.5 - 5</td>
<td>P1 15 - 30</td>
</tr>
<tr>
<td>F2 50 - 70</td>
<td>P2 5 - 16</td>
<td>P2 30 - 160</td>
</tr>
<tr>
<td>F3 70 - 90</td>
<td>P3 16 - 50</td>
<td>P3 160 - 510</td>
</tr>
<tr>
<td>F4 90 - 115</td>
<td>P4 50 - 160</td>
<td>P4 510 - 820</td>
</tr>
<tr>
<td>F5 115 - 140</td>
<td>P5 160 - 500</td>
<td>P5 820 - 2800</td>
</tr>
</tbody>
</table>

damage descriptors

F0 - light damage: some damage to chimneys; branches of trees broken; shallow-rooted trees pushed over; sign boards damaged

F1 - moderate damage: roof surfaces peeled off; mobile houses pushed off foundations and overturned; moving cars pushed off the road

F2 - considerable damage: roofs torn off frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light-object missiles generated

F3 - severe damage: roofs and some walls torn off; well-constructed houses overturned; most trees in forested areas uprooted; heavy cars lifted off the ground and thrown around

F4 - devastating damage: well constructed houses levelled; structures with weak foundations blown some distance; cars thrown and large missiles generated

F5 - incredible damage: strong frame houses lifted off foundations and carried considerable distances to disintegrate; automobile-sized missiles fly through the air in excess of 100 m; trees debarked, and incredible phenomena will occur
5.2 Characteristics of extreme winds

The relevant characteristics of windstorms that affect the extent of damage are highlighted in the following subsections.

5.2.1 Magnitude of wind speed

The most critical characteristic of strong winds that directly affects the extent of damage, is magnitude of wind speed. Following an analysis by Milford (1985), a design peak wind speed of 40 m/s (with 50 year return period) has been specified for most areas of South Africa in SABS 0160 (Figure 5.2).

(A wind speed of 39.4 m/s was recorded in February 2000 in Fort Beaufort before the actual recorder was ripped off and displaced. A time trace is presented in Figure 5.3a.)
Winds generated by mature fronts and frontal cyclones typically dominate the coastal regions and in some cases also the interior (mid-latitude lows). While frontal and tropical cyclones do not generate winds of significant speeds in South Africa (i.e. typically well below 40 m/s at elevations below 10 metres), they may produce squall-lines, thunderstorms and tornadoes which give rise to more severe winds.
The highest wind speeds affecting the built environment in South Africa are typically related to severe thunderstorm activity. The strong winds could be due to an outflow from the thunderstorm's supercell (often as short but powerful frontal bursts, so-called leader gusts, as depicted in Figure 5.3b (Weringa, 1973)) or severe downdrafts (microbursts) and tornadoes generated within the supercell. In Figure 5.3c a time history of the wind speeds recorded in a microburst is presented (Liu, 1991).

Figure 5.3b: Two time traces of thunderstorms with a leader-gusts
For several reasons the direct measurement of extreme wind speeds in thunderstorms is difficult and even more so in localised events like tornadoes and downbursts. Comprehensive overseas research based on structural assessment and calculations of damage and also photogrammetric measurements of movement of debris suggest, however, that wind speeds up to 150 m/s close to ground level, can be generated in tornadoes. One such estimate made on the basis of a South African tornado event suggested a wind speed of more than 100 m/s as discussed in Section 3.2.

Another relevant parameter related to the wind magnitude and the resultant amount and type of damage is illustrated by comparing Figures 5.2 and 5.4, which present maps of maximum mean hourly wind speeds and peak gust wind speed for South Africa. This parameter (typically referred to as the Gust Factor) describes the ratio of the peak over the mean wind speed (i.e. the gustiness of the flow). It can be seen that in the coastal areas (i.e. in mature gale winds) the GF is 1.6 (i.e. 40m/s / 25m/s) and in most inland areas (subjected to thunderstorms) the GF is 2.0 (i.e. 40m/s / 20m/s).
The issue of the magnitude of damaging winds has direct implications for the risk model which is proposed in the current dissertation. Damage to non-structural amenities occurs at wind speeds lower than the extreme winds used for codification purposes and due to the nature of the proposed model, less emphasis will be placed on extreme wind speeds than on the typical ranges of wind speeds associated with the various types of strong wind events.

5.2.2 Duration

The duration of the wind affects the amount and type of damage to structures.

Short duration extreme gusts may severely weaken the structure but the time span might be insufficient to cause the final collapse. Such situations have in fact been observed during post-disaster evaluations of sites affected by tornadoes and microbursts.

On the other hand a wind of relatively lower magnitude, which persists over extended period of time, can lead to progressive structural damage (often due to fatigue). This is frequently the case with south-easterly winds in the Western Cape and also with large frontal events where the translation movement is relatively slow. Figure 5.5 depicts the time history of the...
pressure drop due to a passing frontal cyclone lasting about 8 hours and Figure 5.6 depicts a typical 24-hour time trace of a spell of south-easterly trade wind in Cape Town.

Figure 5.5: Time history of pressure caused by a frontal cyclone (Strand, 29 Aug. 1999)

Figure 5.6: Time trace of a typical South-Easter (Cape Town International Airport, 2 March 1994)

Due to the spatial nature of the proposed model, the issue of the duration of strong winds will not be considered. By doing so, the model ignores the question of the application of loading in time and therefore assumes that all types of wind events will be applied in the same manner.
5.2.3 Wind speed probability of occurrence

The probability of wind speed occurrence represents the number of times within a stipulated time period that a wind speed of a certain magnitude will occur in a certain area. This information is usually derived from a statistical analysis of the data obtained from recording instrumentation placed within the area. Various extreme value distribution techniques are used (e.g., Parent, Weibull, Type I, Type II). An example of such distribution is presented in Figure 5.7 for the annual maximum hourly mean and peak gust wind speeds in Cape Town (Milford, 1987).

![Figure 5.7: Probability distribution of mean and gust wind speeds for Cape Town International Airport](image)

The above approach assumes that large geographic regions are homogenous and the probability of wind speed occurrence derived for a specific location is also applicable to other locations within the region. This philosophy forms the basis for wind loading design where the loading for a structure is calculated using wind speeds obtained from an extreme value analysis for various return periods.

For large regions comprising various climatic zones, the application of wind data from a single recording source is questionable.
It is important to mention that for the proposed model the issue of wind speed occurrence will be considered in a completely different manner to that used for codification purposes. In the proposed model, the generic footprints of wind speeds will be identified for various types of strong wind events. This is done in order to overcome the problem of poor representivity of the data from a sparse network of recording stations as well as to provide a more suitable platform for dealing with spatial relationships and all types of amenities.

5.2.4 Geographical distribution

Typically, extreme wind events have strong regional characteristics governed by geographical macro-climatic conditions. For example, analysis undertaken by Huang et al (1999) suggests that most of the expected loss due to hurricanes in the USA is limited to a stretch 20 kilometres inland of the coast, due to the rapid reduction in wind speed that occurs further inland.

The optimal way of determining the geographical distribution of extreme wind events within a specific geographical region or country is to capture and analyse the distribution of recorded and documented events (e.g. Schroeder and Smith, 1999; Sparks and Huang, 1999). An example of such geographical distribution of confirmed tornadic events in South Africa (between 1905 and 1997) is presented in Figure 5.8 (Goliger et al, 1997). Development of such data requires extensive (i.e. time consuming and expensive) searches and analysis.

Another, more generic, approach is to analyse the climate of a region (country) and to identify the relevant characteristics affecting the potential for the development of severe wind events. Such information enables the development of a geographical map of extreme wind zones. An example of such a map depicting the regions of various types of severe thunderstorms in the USA is presented in Figure 5.9 (Kelly et al, 1985).

For South Africa, the starting point for such generic analysis is a map of the climatic regions (Schulze, 1965).
Figure 5.8: Geographical distribution of tornado events, 1905-1997

Figure 5.9: Climatologically homogenous regions for the study of severe thunderstorm occurrences in the USA
In view of the significant climatic differences in South Africa, the issue of geographical prevalence of strong wind events is important but not reflected in the wind codes. The prevalence of various types of strong wind events forms the basis and one of the major assumptions of the proposed risk model. It is assumed that severe strong wind events can be divided into various types of events and that the occurrence of each type of event is limited to a specific geographic region.

5.2.5 Spatial extent of wind events

The spatial extent of various types of extreme wind events has a pronounced influence on the scale of potential disasters and, therefore, their social and economic impact. In this context, it is fortunate that the spatial extent of the most devastating wind phenomena (e.g. tornadoes and microbursts) is relatively small. For example a spatial analysis of insurance claims related to one USA tornado indicates that the damage was limited to a distance of 800 metres from the centre of the trail (Kruse et al, 1999).

In South Africa two basic types of strong wind events can be identified, namely:

- Inland,
- Coastal / frontal.

(The inland winds originate from severe thermal / convective activity developing in hot weather and the coastal winds are due to frontal low-pressure systems.)

Each type of strong wind event has markedly different spatial characteristics. The inland wind events are usually fairly localised (i.e. limited) in extent, comparable to the geographic extent of urban settlements (i.e. of a metropolitan area or a suburb), whereas the coastal events are usually related to broad climatic fronts extending for several hundred kilometres. Most coastal events do not, however, penetrate more than 50 to 100 kilometres inland.

The set of assumptions regarding the spatial extent of typical strong wind events in South Africa forms one of the basic hypotheses of the proposed risk model. Similar assumptions also form the basis of the climatic weather analysis and predictions carried out by the South African Weather Service.
5.2.6 Changes with elevation

Typically the magnitude of wind speed increases with elevation above the ground level. The rate of this increase depends on several factors, but mainly the roughness of the terrain. This is one of the major concerns of boundary layer theory and several simplified algorithms are available for typical types of terrain (i.e. roughness). The algorithms can be broadly divided into those based on the power-law and logarithmic formulas.

It is important to note that the above algorithms constitute gross simplifications of the full-scale situation and represent generic types of terrain roughness only. In a built-up terrain, or one that is influenced by a dominant topography, the vertical profiles are strongly influenced by the surface features, and they can only be determined using wind-tunnel technology.

The issue of changes in wind speed with elevation is of secondary importance to the proposed risk model. It has been assumed that in principle the generic wind speeds quoted in the risk model refer to the peak wind speeds at the universally accepted standard elevation of 10 metres above ground level used for the recording of full-scale winds.

5.2.7 Seasonal variations

Typically, strong wind events have pronounced seasonal characteristics.

Most obvious is their occurrence, for example in South Africa thunderstorms over Gauteng occur in summer. Other seasonal characteristics of winds refer to their direction or strength. For example, the south-easterly winds in the Cape Town area typically occur in the summer months and north-westerly winds in winter. Furthermore, most of the severe thunderstorms over Gauteng occur in spring, early summer and late summer.

Also important, from a disaster management point of view are other seasonal characteristics of strong winds like the fact that the south-easterly winds are ‘dry’ as opposed to the north-westerly ‘wet’ winds, or the fact that severe thunderstorm events over Gauteng are often accompanied by hail.

The seasonal characteristics of strong wind events may influence disaster management activities on a regional or national scale in respect of the allocation of resources. Prediction of seasonal wind damage patterns (i.e. loss) enables disaster authorities to optimise the allocation of financial resources. Furthermore, the seasonal variation in occurrence of
damaging wind events will also allow the determination of the demand (in time domain) for specific reserves of relief material (i.e. the explicit need for tents during the rainy season).

The seasonal characteristics of the occurrence of strong wind events is not explicitly considered in the proposed version of the risk model although the model could be extended further to account for this. However, a broad correlation between the seasonal characteristics for various types of wind events emerges from the model.

5.2.8 Directional characteristics

Some strong wind events have dominant directional characteristics. This typically refers to large, frontal types of events and not to thunderstorms. On the other hand even relatively small events like tornadoes indicate directional preference of movement. USA research shows that about 90% of tornadoes travel in a generally eastward direction. Similar analysis undertaken for South Africa (Goliger et al, 1997) indicates the percentage to be more than 80%.

The direction of strong winds may not necessarily influence the amount and occurrence of subsequent damage. For example Sill and Matthewson (1999), who investigated the relationship between wind direction and damage caused by hurricanes, concluded that as the hurricane passes, wind direction and magnitude have opposing effects, (i.e. the lower the speed, the greater change in direction). Furthermore, in general a change in wind direction results in a surprisingly small increase in damage and could be ignored (especially within the 'eye' of the path).

In South Africa all coastal winds have strong directional characteristics and, to a lesser extent, winds in the interior, as presented in Figure 5.10 (Kruger, 2001).

The directional characteristics of strong wind events in South Africa are not investigated in the current study and are not considered in the proposed risk model. By ignoring the effects of the directional characteristics of dominant winds, one assumes the same likelihood of occurrence from all possible wind directions. For the design of individual structures such an assumption is generally of a conservative nature. It is stated in BS 6399 (1997) that, on average, directional design reduces the design wind loads on structures by about 12%.
Figure 5.10: Wind roses for South Africa
5.3 Local and terrain factors affecting the wind field

5.3.1 Topography

The wind characteristics measured at a specific recording station within an area of concern are modified by local topographical features, vegetation and built environment (due to exposure and shielding). This applies to all the factors discussed in Section 5.2 (e.g. magnitude, wind profile, wind speed occurrence, etc).

In certain situations the influence of local factors on consequent wind damage can be significant. For example, Walker et al (1987) assessed the effects of topography on the wind field of cyclone Winifred in Australia and suggested that there was almost a 40% increase in the wind speed affecting a house on top of a 70 m ridge.

For a specific area or locality the dominant topography can either decrease (due to shielding and the flow reversal phenomenon) or increase (due to accelerated up-slope flow and over the ridge) the wind speed magnitude.

Several research studies have been conducted throughout the world with the aim of quantifying the effects of topography (e.g. BRE Digest, 1984; Hertig, 1987). Comprehensive prediction models on the influence of topography are available and some have been incorporated into codes of practice (BS 6399, 1997; ASCE, 1996). It has to be noted that all these methods are highly simplistic and refer to idealised cases of flow over smooth two-dimensional hills where no separation zone of the flow is present.

These are clearly not applicable where the topography is complex and three-dimensional like that dominating the city centre of Cape Town. In such cases, any full-scale measurements to study changes in wind characteristics due to local conditions are not feasible and the only practical and scientifically based method of predicting this influence is wind tunnel technology.

For several years the CSIR's wind-tunnel laboratory has conducted comprehensive tests to predict wind conditions at various places within the Cape Town Metropolitan area.

Figures 5.11a and 5.11b present examples of the results of wind-tunnel studies into the influence of the dominant topography in Cape Town affecting the quantitative and directional characteristics of wind approaching the Central Business District and the port (Goliger et al,
In Figure 5.11a, profiles are presented of the selected wind quantities measured for one specific horizontal traverse and at several locations in front of the mountain, on its top and along the lee-side towards the city centre. It can be seen that at the selected locations along the slopes of the mountain, on its top and downwind towards the city centre, the magnitude of all parameters of the profiles changes significantly.

Figure 5.11b presents the directions of local winds at various locations over the city centre, subject to south-easterly winds blowing from an azimuth of 170 deg. Again it can be seen that the directions of the local winds at different places are highly variable.

From the disaster management point of view it is important to note that the presence of a dominant topography can modify the wind vulnerability of those areas influenced by this topography. A good example of this is the trail of the 1997 tornado on the Cape Flats, which 'bounced-off' the slopes of the Table Mountain and progressed towards the area which was subsequently devastated. In the Western Cape it is well known that although frontal events typically envelop large areas of land, the severe damage is often limited to widely scattered locations. This selectiveness of damage can be attributed to the influence of the dominant topography.

The presence of topography influences the foot prints and inland penetration of coastal winds as discussed in Chapter 9. This issue is not investigated in the current dissertation and is deferred for further studies.
Figure 5.11a  Profiles of selected wind quantities affected by a dominant topography

- Flow azimuth 170°
- Dimensions not to scale
- mm - refers to wind-tunnel model scale
- m - refers to the full-scale data

City
C.B.D.
coast
Figure 5.11b: Directional distribution of local winds in the lee of dominant topography
5.3.2 Other structures

The changes in wind characteristics that result from the presence of a built environment are also significant and a great deal of research has been carried out on this (e.g. Cermak et al., 1995; Tieleman, 1992). Due to the infinite possibilities of the 3-D permutations in the form of the built environment, it is not possible to develop reliable prediction models of the influence of other structures within the urban (and to a lesser extent sub-urban) context. The only reliable method of predicting this is wind-tunnel modelling.

In Figures 5.12a and 5.12b examples of experimental results obtained at the CSIR's boundary-layer wind-tunnel laboratory are presented. Figure 5.12a presents the directional distribution of local winds at the base of a tall building (Goliger and Richards, 1997). It can be seen that the flow pattern is complex and the directions of local winds coincide with the free-stream wind in only a few places. Figure 5.12b demonstrates the influence of the built environment on the probability of wind speed occurrence by comparing two specific locations within an urban development at an elevation of 2m (Goliger and Milford, 1991). It can be seen that the wind speed probability distributions for both locations differ significantly.

Figure 5.12a: Directions of local winds at the base of a tall building
These distributions were obtained from the integration of the statistics of long-term climatic data from a Weather Bureau recorder positioned some twenty kilometres away with a set of data measured in a wind-tunnel. The integration process was based on the principles of boundary layer modelling (Goliger and Milford, 1988) and the results of topographical studies (Goliger et al 1990).

As with topographical effects (Section 5.3.1), the issue of wind flow characteristics within the built environment is not considered in the proposed risk model.

5.4 Distribution of assets

The geographical distribution and density of assets as well as the relationship between the replacement costs of various types of assets, affect the spatial probability and extent of damage. For example for a relatively small area with dense development, the spatial probability of an extreme wind event might be small, but the consequences of one striking the area could be significantly larger than that of a large area with a low density of development.
Several factors affect the distribution of assets, for example:

- distribution of population,
- distribution of wealth,
- political stability,
- accessibility of land,
- accessibility of transportation routes, and
- general industrial growth.

Depending on the general economic growth and trends within a geographical region or country, these factors can be highly influenced by the time factor.

Petak and Hart (1979) analysed the statistics of exposure to natural hazards for various types of structures in the USA. The distribution of assets is given below:

- 54% housing,
- 14% manufacturing / retail / finance type structures,
- 14% local and national government,
- 11% transportation utilities, and
- 7% other, including 1% farming.

It can be seen that housing constitutes the single largest national asset and the same would probably apply to South Africa. This can be extrapolated further by posing a hypothesis (opinion) that in the developed countries of the world, a fair correlation between the distribution of assets and the general population distribution can be expected. This might be less applicable to developing countries including South Africa.

It is stressed that due to the nature of the current dissertation, those aspects of the model that relate to the distribution of human built development and assets are not investigated. It has to be noted, however, that an important characteristic of South African development and asset distribution is the disparity between formal and informal development. This has to be kept in mind in any such consideration.

5.5 Resistance of structures

The damage to structures due to windstorm events depends on wind hazard (i.e. risk) and the resistance (i.e. vulnerability) of structures. Broadly speaking, the damage potential is the product of risk and vulnerability (Davenport, 1997).
Hazard is described by the intensity and extent of the windstorm, the time history of damaging winds and risk of their occurrence. The issue of structural vulnerability and vulnerability function has been discussed in Section 3.4.3.2.

In developing countries (including South Africa) a large proportion of structures (and therefore also assets) have little or no engineering input and these also have to be represented in any risk assessment. In Figure 5.13 a schematic sketch of a generic relationship between the magnitude of wind speed and the degree of damage for both types of structures (i.e. engineered and non-engineered) is postulated.

![Figure 5.13: Idealised schematic comparison of wind vulnerability of engineered and non-engineered structures](image)

An assumption is made that the non-engineered structures will fail at lower wind speeds than the engineered structures. Furthermore, at low magnitudes of wind speed the initial insignificant damage occurs, and the subsequent incremental increase in damage with increases in wind speed is relatively small (i.e. low gradient of the curves). It can also be noted that the smaller increase in the wind speed (i.e. steeper curve) characterises the progressive damage to non-engineered structures.

Due to the nature and objective of the current dissertation, the aspects of the model that relate to the resistance of structures were not investigated.
5.5.1 Formal and informal development

In developed countries most, if not all, new structures have to comply with a minimum set of design specifications and / or regulations. In many cases the regulatory requirements are also applied retrospectively in that existing structures have to be modernised or upgraded in order to comply with current safety and structural requirements.

The enforcement of these principles in developing countries is much more difficult, if not impossible. As a result, in many ‘countries of the South’ two mainstream types of construction markets and sectors coexist (i.e. the formal and informal).

In South Africa, the best example of this situation is the housing sector in which, for various reasons, no standard requirements have historically been enforced in the rural areas. Furthermore, even within urban areas a sharp contrast between the relatively high standards of formal housing and dismally low standards of informal (often squatter) areas is apparent.

A detailed discussion on various aspects of standardising (including structural issues) informal and low-income housing in South Africa is included in Boutek’s (formerly NBRI) publication (NBRI, 1987).

5.5.2 Formal structures

Formal structures usually include some form of engineering and architectural inputs and their final strength is determined by several contributing factors, which can be broadly grouped under:

- design,
- approval and
- construction stages / activities.

In the author’s experience, wind-related failures of structures in South Africa can often not be limited to one of the above activities but are rather due to a combination of errors committed across these activities.

5.5.2.1 Planning and design

The planning and design process includes several role players and activities which affect the final strength of the proposed structure. In the author’s opinion the dominant factors include:
- locality of the structure (i.e. its geographical location) and the character of the immediate surroundings (Port Elizabeth vs. Johannesburg or city centre vs. outskirts),
- general form of the structure and its wind vulnerability (e.g. mast vs. tower, higher vs. broader building or concrete vs. steel structure),
- in the case of housing, the geometric form of the roofs and walls, the amount of openings and internal divisions,
- structural system, technology and materials (e.g. composite materials for walls vs. brickwork),
- access to quality design information and procedures (i.e. reliable codes of practice and building regulations), and
- quality of the design including the expertise of the team, adherence to sound processes and access to acceptable technical support,

5.5.2.2 Approval

Assuming a satisfactory design, the quality of approval process is of relatively lesser importance. On the other hand, however, the approval process plays a major role in detecting and rejecting poor or unsafe designs and by doing so protecting the interests of community or client and minimising, among other things, the risk of wind damage. Two factors that affect the wind vulnerability of structures can be identified as:

- the technical expertise of the local authority (i.e. sufficient number of qualified and experienced engineering staff), and
- the existence of adequate review and approval processes and the degree of will to enforce compliance. (It is our experience that this issue can become critical in South Africa where in some cases the developers of structures in windy places like Cape Town or Port Elizabeth could force wind-safety related concessions from local authorities in order to minimise the costs of a development.)

5.5.2.3 Construction

Construction processes are usually complex and often involve not only the actual construction site activities but also the material supply chain including prefabrication plants. Several factors that influence the strength (i.e. wind resistance) of structures can be identified as:

- the scheduling and sequencing of activities,
- the quality of processes and management,
- the quality of materials (including the accuracy of prefabricated elements),
\begin{itemize}
  \item the quality of workmanship, and
  \item the quality and expertise of the supervising staff.
\end{itemize}

\subsection*{5.5.3 Informal structures}

The informal construction sector typically refers to the erection of human shelter and / or other types of outbuildings. An aerial photograph of a typical informal settlement is presented Figure 5.14.

In most cases, none of the factors which have been listed in Section 5.5.2 are applicable. The author's experience gained during various site inspections and investigations of wind damage to informal human settlements reveals, however, that several common factors influence the wind resistance of informal dwellings and these are discussed in the subsections which follow.

Figure 5.14: A typical informal development
5.5.3.1 Locality
As for any other structures, the wind vulnerability of informal settlements depends on their locality. For example, the presence of dominant hills may provide shielding for certain wind directions but may also generate significant wind loads under the berg wind conditions. Furthermore, where structures are located on mountain slopes and depending on the steepness of and position along the slope, the wind speeds (i.e. loads) could be reduced or increased. Figure 5.15 presents an example of an analysis of a proposed township in South Africa in order to determine the character of the surrounding terrain (i.e. the approaching wind conditions) for various wind directions (DFG, 1998).

Even in the case of frontal cyclones that are characterised by relatively low wind speeds, the local topography can compress and funnel strong airflows to produce very high local winds (Golden and Snow, 1991). This situation is also evident with south-easterly winds in Cape Town, where the relatively shallow airflow from the sea is blocked by the dominant topography around the city bowl and restrained by the upper level air in the vertical direction (Hunter, 2000).
Figure 5.15: Analysis of approaching terrain / wind conditions
5.5.3.2 Density and shielding
In urban and suburban areas of South Africa, a shortage of available land is evident and informal settlements tend to cluster closely together and densify with time. Such situation is presented in Figures 5.16a and 5.16b which compare the extent (density) of Brink's Vlakfontein township in 1992 and 1996 (DFG, 1998).

As a result of densification and growth, the shelter units 'inside' the settlement can experience substantial wind protection due to the presence of the neighbouring shelters, but not the units at the perimeter of a development. The issue of changes in wind exposure with time has been raised in Kasperski et al (1999).

5.5.3.3 Geometrical form
In line with the basic principles of fluid dynamics, smaller objects and those with rounded-off geometries generate smaller wind loads and are, therefore, less prone to wind damage. The traditional African shelter followed those principles and was typically of a 'squat' and round form, with conical or domed roofs (Goliger, 2001) as presented in Figure 5.17a. Figure 5.17b presents a rondavel, which escaped unscathed while the neighbouring rectangular structures with flat roofs were demolished by a strong wind event.
Figure 5.16a: Layout of Brink's Vlakfontein township (1992) (based on photo-interpretation)
Figure 5.16b: Layout of Brink’s Vlakfontein township (1996) (based on photo-interpretation)
Figure 5.17a: Traditional housing unit – rondavel

Figure 5.17b: A rondavel escaped unscathed while the neighbouring rectangular-shaped structures were destroyed (Bethany, Eastern Cape, Dec. 1997)
In the last 20-30 years corrugated metal sheeting has been used to an increasing extent in informal squatter developments (Figures 3.10 and 5.14). Sheets are used not only for the construction of roofs but also for walls.

5.5.3.4 Permeability of roofs

The issue of the permeability of roofs is relevant to both informal and formal building structures. Traditional methods of covering the roofs with grass, slates, tiles or timber, has proved to be beneficial both in respect of thermal comfort and also in the inherent ability to withstand extreme wind gusts of short duration. This is as a result of their permeability, which enables instantaneous equalisation of pressures. For these types of roof, damage is typically limited to selected areas or individual tiles (Figure 5.18a).

South African experience suggests that this is particularly relevant to thatched roofs which despite being relatively lightweight, often prove to be fairly resistant to extreme wind loads. Similar observations have been made in India (Somayaji et al, 1995). Figure 5.18b presents fairly insignificant damage to the thatched roof of a house which happened to be in the centre of a tornadic trail (Goliger and Edwards, 1994). The magnitude of the extreme negative pressure was such that the water was sucked out of a swimming pool some 20 metres away.

Figure 5.18a: Edge roof tiles removed by wind (Bellville, Dec. 1996)
In contrast, modern roof sheeting which is widely used in the informal sector of human shelter, offers several benefits (e.g. ease of construction, watertightness and minimal maintenance) but it is also disadvantageous because of its poor performance under extreme wind conditions, due to its lack of permeability which often leads to the failure of the entire roof (Figures 3.1f and 3.1g).

Figures 5.18c and 5.18d present roof failures of large modern structures. The damage shown in Figure 5.18c is due a corner vortex. The venting louvers of the parapet wall which were provided, proved to be unsatisfactory. Figure 5.18d presents a case in which an entire portion of a large-span barrel-vault roof has been torn off despite significant allowance for venting of the entire roof.
Figure 5.18c: Damage to the roof sheeting of a large commercial building

Figure 5.18d: A missing portion of sheeting of a large-span roof due to wind action
5.5.3.5 Fixing of sheeting

The roofs of informal houses constructed with sheeting are typically of single pitch and nearly flat. The fixing of the sheeting constitutes a significant factor affecting the performance of such shelters.

Inadequate fixing may lead to removal of individual or several sheets. Adequate fixing typically prevents this, but may introduce the risk of displacement of the entire roof. The author's discussions and investigations with the members of informal (and low-income) communities revealed that this issue constitutes a technical-economical controversy. Some of the inhabitants in windy townships in coastal cities prefer relatively poor fixing of sheeting rather than losing the entire roof.

In many cases they would also select a traditional way of preventing uplift by loading the roofs with rocks or sand-bags (Figure 5.19). This eliminates the need to punch holes, increases the watertightness, reduces the effect of fatigue under long-term wind loading and also allows for flexibility when modifying the form of dwelling.

Figure 5.19: Traditional method of preventing roof uplift
5.5.3.6 Extent of unsupported surfaces and walls

By and large, informal development involves low-income socio-economic groups seeking minimal standards of accommodation at minimal cost. These overriding factors lead, among other things, to a constant drive to reduce material inputs.

One of the ways of reducing the use of structural materials is to omit internal subdivisions inside the shelter. Such an approach not only compromises the privacy of the inhabitants, but also drastically reduces the rigidity of the dwelling (i.e. the horizontal bracing of external walls).

Despite this, an incremental development policy for pre-engineered housing units has been formally recognised in recent years by the state agencies. One of the models used is so-called core-housing where the external shell of a dwelling unit is built to its full extent and fitted with basic services, but without dividing walls. The owner is then expected to add these at a later stage, depending on his / her social and functional requirements and economic ability. Another approach is to design the final form of a house but to erect only a portion of it and again, the owner is expected to finalise the extension at a later stage. In such a case the aerodynamic aspect ratio of the erected structure could be very different from that used in the initial design (see Figure 5.20).

An example of such a pre-engineered housing system is presented in Figure 5.20, and Figure 5.21a shows one such unit which was devastated by a downburst, (Matsulu, December 1991). The failure, leading to the death of one person, was clearly triggered by the collapse of a large unsupported gable wall. Figure 5.21b presents a similar housing unit which withstood the extreme wind loading. This unit had been fitted with an additional stiffening pillar.
Figure 5.20: Plan of a core housing unit
Figure 5.21a: Wind devastation of a pre-engineered housing unit (Matsulu, July 1992)

Figure 5.21b: Additional stiffening pillar to support a large gable wall
From the risk damage point of view it could be argued that the internal walls (extension of the house) would be added within a few years, during which time the probability of an extreme wind with a return period of 1 in 50 years is small. In practice this may not be the case, as the internal walls may never be erected.

Another typical problem of informal housing and some low-income building systems is the lack of ceilings which provide horizontal support to the top of the walls (i.e. allow for a transfer of the horizontal forces generated by wind).

5.6 Mechanisms of failure and extent of damage

5.6.1 Content of the built environment

Each country, including South Africa, has its own unique pattern, content and technologies related to the built environment. These depend on several factors including: the climate, economy, culture, availability of resources, etc.

The standards of design, construction practices and technologies in various countries could lead to marked differences in wind resistance. Drayton et al (1999) suggest that in Europe wind speeds between 40 and 45 m/s cause only minor damage to roofs, which constitutes only a few percent of the total value of individual buildings. By contrast, experience gained in the structural evaluation of buildings in South Africa, carried out by the CSIR (Forbes, 2000), indicates that most housing would fail under substantially lower winds.

One could also consider the differences between the typical housing systems used in the USA and South Africa. The majority of the USA population is housed in various types of lightweight systems consisting of a structural frame (typically timber or metal) and panels of sheeting. Furthermore, a large proportion are so-called mobile homes, typically without foundations and little or no structural connection to the ground. By contrast most of the formal housing in South Africa consists foundations, 220 mm brick walls and roof trusses tied to the walls. In terms of structural behaviour and resistance, the differences between these systems could be substantial.

Taking the above into account, it is the author's belief that these differences have influenced the statistics of the South African tornadoes (Goliger et al 1997). This is based on studies of tornado occurrences throughout the world (Goliger and Milford, 1998), South African
involvement in the work of the International Task Force on High Intensity Winds (1995 and 1997) and interactions with researchers in the USA.

In the absence of any other consistent and internationally recognised classification systems of damage, the Fujita (1973) categorisation had to be used, as presented in Table 5.1. This categorisation has been developed on the basis of the damage recorded in the USA, and because of the differences in construction practices, this could have resulted in a consistent underrating of the severity of South African tornadic events.

5.6.2 Long- and short-term loading

There are two basic modes in which damaging wind loads are applied to structures. These can either be high wind speeds that last a long time and are due to cyclones or coastal gales, or sudden extreme winds of short duration due to thunderstorms, downbursts and tornadoes.

As discussed in Section 5.2.2 the duration of large depression fronts and coastal gales can easily extend over several days. Such spells of wind can include several periods of relative calm and usually maintain a fairly constant direction.

Even in frontal cyclones, movement in horizontal plane is relatively small, and a specific area can be affected by high magnitude winds for a period of several hours (typically 3-6 hours). Furthermore, as the cyclone passes over the area, the direction of the wind changes slowly and structures would experience variable angles of wind attack that produce the worst loading combination on a particular element.

Long-term loading usually affects roof sheeting systems of poor materials and workmanship, typically with respect to the fixing of the sheeting. Unfortunately, the roofing system compliance tests used in most countries are usually static in nature and do not simulate the effects of the fatigue. The importance of this issue has been raised by McDonald (1995).

Short-term loading due to events like downbursts or tornadoes produce instantaneous extreme loads over the entire structure. In some cases these loads may exceed the 1 in 50 year return period winds specified in the codes of practice. On the other hand, however, the short duration of the extreme wind action is a mitigating factor.
5.6.3 Large and engineered structures

In South Africa, like anywhere as elsewhere, the structural design of large and costly or higher-risk structures like tall buildings, chimneys or industrial complexes is carried out with due consideration of the wind loading specification of the relevant codes. In the event of extreme wind events, the damage to such structures is typically limited to small areas, individual external glazing, sheeting or secondary attachments, and not the structural load-carrying components.

Mehta et al (1991) suggest that in the USA (apart from special structures like hospitals) the above statement is applicable to high-rise buildings (i.e. more than 6 storeys) and industrial structures but not to low-rise commercial buildings (typically lightweight), schools, warehouses and housing units.

However tornadoes and downbursts can inflict significant damage irrespective of the type of structure. An extreme example of such damage is the case of the torsional deformation of an entire high-rise steel-frame building (Mehta et al, 1971; Wen 1975). Few selected local examples include:

- The collapse of a 25 metre high floodlight (Figure 5.22) and a grandstand at a sports centre in Matsulu (11 December, 1991).

- A relatively weak tornado, F1 on the Fujita scale (Goliger et al, 1999) of 21 October 1999 damaged a significant portion of curtain wall and gates of an industrial complex (Figure 3.1p).

- A large number of towers from seventeen independent transmission lines devastated by the Welkom tornado of 20 March, 1990 (CSIR, 1992), Figures 3.1q and 3.1r.

- The top section of an MTN transmission mast bent by the Heidelberg tornado of 21 October 1999 (de Conning et al, 1999).
5.6.4 Low-rise and residential structures

As in many other countries, most of the wind damage to structures in South Africa relates to human shelter and its surroundings.

Based on the experience gained during several post-disaster evaluations of wind damage to houses, the author proposes a division into four stages of damage (related to the extent of the damage). These are highlighted in the following subsections.

5.6.4.1 Minor damage

Minor damage is typically limited to roofs. Frequently it refers to the removal of selected roof tiles and local uplift of roof sheeting, typically along the eaves and ridges. This allows for immediate pressure equalisation and prevents further uplift. Although this has no structural implications, it can lead to permanent damage of ceilings and the contents of the house, if the storm is accompanied by rain.

Examples of minor damage to roofs are presented in Figures 3.1c and 3.1d.
5.6.4.2 Substantial damage
In certain cases the action of severe winds can introduce significant damage to roofs. This is typically for sheeted roofs, as well as tiled roofs with a PVC underlay, which are fairly impermeable and prevent the equalisation of pressure. Under extreme winds this may result in significant damage to roofs including the failure of fixings, breakage and deformation of the entire sheeting and buckling of trusses. If the fixing of sheeting to purlins is sufficient, this may result in the destruction of parts of, or the entire roof structure. An example of such damage is presented in Figures 3.1f and 3.1g.

Such damage is usually associated with the destruction of other components of the built environment like free standing walls, outbuildings, vegetation, vehicles, telephone and transmission lines (Figures 3.1b and 3.1e).

5.6.4.3 Serious damage
Serious damage involves roofs, portions of, or entire walls. In some cases as presented in Figure 3.1h, the upper portions of the walls are ripped off due to the uplift force generated over the roofs and transferred to the walls via the roof ties. In other cases entire walls are blown over or sucked outwards as presented in Figures 3.1i and 3.13a. This can also include the failure of concrete elements as presented in Figure 5.23 (May 1949 Bronkhorstspruit tornado, courtesy Pretoria News).

The extensive damage to the walls of buildings usually coincides with the total destruction of garages, outbuildings and garden walls.
5.6.4.4 Complete devastation

In extreme cases, the total annihilation of building structures can occur. Fortunately this degree of devastation is typically of a selective nature. It does not apply to all buildings in the neighbourhood, but is rather related to the vulnerability of particular structures or their exposure in relation to the passage of the extreme gusts.

An example of such a situation is shown in Figure 3.11 in which the concrete floor, a few toilets and foundations were the only remains of a prefabricated building and yet the neighbouring pavilion only lost its roof (Lunt et al, 1987). An example of the total devastation
of an informal settlement due to the November 1952 Albertynsville tornado is presented in Figure 5.24.

Figure 5.24: Devastation of Albertynsville (Nov. 1952)

5.6.5 Flying debris

A considerable portion of damage to structures due to extreme winds can be attributed to flying debris and this has been confirmed by several research studies (e.g. Saffir, 1971; Mahon et al 1979; McDonald, 1990). The number of deaths and injuries is usually low, because people caught in extreme wind conditions typically seek a sturdy shelter. On the other hand, however, in some environments (e.g. informal settlements) the structures are often not able to maintain their integrity and to provide adequate protection.

A significant amount of air-borne debris can be generated under extreme wind conditions. The immediate adverse consequences for the structures from which they originate, relate to the:

- openings which are created which allow easy rain penetration, and
- internal pressures in the buildings that build up as a result of the openings, and this increases the net outward loads on roofs and walls.
The size of debris can range from dust particles to components of building structures (Figure 5.25 – courtesy of the Cape Argus), trucks and railroad coaches (Goliger et al, 1997). Some debris can travel for several hundred kilometres (Davies-Jones, 1995). As an extreme wind progresses, some structures lose their integrity and their elements contribute further to the amount of debris. The impact of flying debris depends upon several factors but mainly:

- the type (size and mass) of the debris,
- wind velocities, and
- the type and configuration of the affected structure.

Figure 5.25: An airborne shed which landed on a car (Cape Town, date unknown)
This is significant in tornadoes where the debris is typically referred as to tornado-generated missiles, with the ability to travel with wind speeds in excess of 100 m/s (360 km/hour). A substantial amount of research has been carried out on the missile impact (e.g. Costello, 1976; Mahon et al 1979; McDonald, 1990) and the development of a Missile Impact Code has been endorsed in some of the states in the USA (ENR, 1994).

One of the interesting research findings (McDonald, 1990) suggests that the conventional wall construction systems used in the USA (frame with masonite, plywood, stucco sheeting) are not able to stop a missile transported by tornado winds, irrespectively of the shape of the tip inflicting the damage. In the author's experience of South African tornadoes, traditional brick walls may typically sustain cracks or partial damage but not total collapse.

Because of the common use of corrugated metal sheeting, a typical characteristic of South African extreme winds (and in particular tornadoes) is a large quantity of sheeting debris travelling over large distances, inflicting death and injury (e.g. Albertynsville tornado, 1952) and damage to other structures. The sheets also end up being wrapped around objects like trees (Figure 3.3b), telephone poles, overhead cables, etc. (Figure 5.26).

Figure 5.26: Roof sheet debris entangled in power line conductors
5.6.6 Wind erosion

One of the mechanisms of structural damage to the built environment caused by wind action which is often forgotten or neglected, is the erosion of foundations. Such erosion usually occurs in non-cohesive and non-saturated soils and in extreme cases it may lead to the undermining of foundations and collapse of walls.

Little information available on this topic in the international literature apart from general data on the drift of snow and sand (e.g. Iverson, 1981; El-Sherbiny, 1983).

Perhaps the most applicable is the research by Bofah et al (1991) in which general design considerations for buildings in sandy and dusty environments are highlighted. These include general rules of sand drift rate, sand erosion, abrasion and accumulation. A graphic interpretation of the empirical relationship between the size of the dry and non-cohesive sand particle and the threshold wind speed (at a height of 10 m) required for its transportation is presented in Figure 5.27. It can be seen that the erosion process may be initiated at wind speeds of about 20 km/hour (5 m/s), at elevation of 10 m.

![Figure 5.27: Relationship between particle size and threshold wind speed of uplift](image)

The issue of sand erosion and the consequent undermining of buildings to the extent that it affects the structural integrity of buildings is applicable to several large township developments in South Africa (e.g. Rosendal, Khayelitsha, Blue Downs), as presented in
Figure 5.28a. At the request of the Minister of Housing, an initial investigation into soil erosion within densely spaced housing developments has been undertaken by the CSIR. The results of the investigations (Van Wyk and Goliger 1996) demonstrated the applicability of wind-tunnel technology to the investigation of wind-induced erosion. Initial characteristics (patterns) were identified as well as the possibility of developing a general set of design principles to optimise the spacing (density) of the units, generic layouts and orientation of the grid with regard to the direction of the prevailing winds.

Note: An unwanted deposition of sand can also significantly affect the functioning of the built environment as presented in Figure 5.28b.

In Figure 5.29a a sample of the wind erosion pattern obtained for one of the investigated layouts and a specific wind direction is presented. Figure 5.29b presents the relative extent of the erosion as a function of the exposure of a unit (i.e. number of shielding units in front of it). (The extent of the erosion was determined by using photographic documentation of sand scour and conversion to CAD poly-line function.)
Figure 5.28b: Unwanted deposition of sand (Cape Flats)

Figure 5.29a: Simulated erosion pattern between buildings
5.7 Human factor

The issue of the wind vulnerability of the human body should also be mentioned as it impacts on the magnitude of loss of human life. Based on international research, it is fair to assume that wind speeds greater than 30 m/s pose a definite risk of injury and death. Obviously this risk will be affected by several factors. The most important one, which usually drastically minimises the extent of human loss, is the fact that during strong wind occurrences people tend to seek any form of protection or shelter. On the other hand, however, it might be argued that in the case of informal human amenities they may not be able to offer satisfactory protection and that is why several extreme wind events in South Africa which have struck informal communities, caused major human loss in terms of injuries and death.
Chapter 6
6 WIND DAMAGE IN SOUTH AFRICA

6.1 Development of a database

In South Africa no statistics on wind-induced damage to the built environment is available, apart from a comprehensive analysis of tornado events (Goliger, 1993 and Goliger et al, 1997).

The development of a wind-damage database has been undertaken as part of the current project. Its initial stage, involved surveys of the archives of South African Weather Bureau, its publications and Climatic Reference System, archives of the State Library and the CSIR. The same methodology was used in the development of a similar database for the USA by the National Oceanographic and Atmospheric Administration - NOAA (Friedman, 1979) and also by Cook (1984) in a survey of wind damage in the UK.

The current database (Microsoft Access) includes about 1 000 events, of which about 30% are classified as tornadoes. Each electronic form contains the information on one specific wind damage event. Two sample forms are presented in Figures 6.1a and 6.1b, and a CD computer disc containing the database is attached. Several generic fields for information were stipulated. These can broadly be grouped as those referring to:

- type of event (frontal vs. thunderstorm etc.),
- time (date, duration, time of the day),
- affected area (location, extent),
- short description of the event,
- references,
- human loss (death, injuries, homeless people),
- damage to various types of structures, and
- financial impact (total and insured loss).
<table>
<thead>
<tr>
<th>id</th>
<th>type of event</th>
<th>classification</th>
<th>tornadoes only</th>
</tr>
</thead>
<tbody>
<tr>
<td>455</td>
<td>thunderstorm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>date</th>
<th>time</th>
<th>duration</th>
<th>map</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980/02/01</td>
<td>16h30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>province</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauteng</td>
<td>Krugersdorp</td>
</tr>
</tbody>
</table>

**Summary**

A freak wind-storm blew off the roofs of 8 houses in Krugersdorp at about 16h30. In Toekomsrus, Randfontein, 7 houses lost their roofs and in Florida Glen, Weltevredenpark, Roodepoort, Birchleigh, Kempton Park and Nigel trees were uprooted and windows were blown away and several houses seriously damaged. Wind speed was estimated to about 100 km/h. Several places were without power and telephone connection. One of the residents in Krugersdorp referred to seeing the biggest and darkest cloud in her entire life and another seeing metal sheets ripped off the roof like a paper. About 150 people were left homeless and power lines were damaged in five areas (estimate 40 houses).

**Notes**

Entry: 16/05/2000 Ursula

**References / Witnesses**

Beeld 1980/02/01

**Human Loss**

- death
- injury
- serious injury / hosp.
- homeless desc.

**Descriptors**

- squatter units
- houses / buildings
- community facilities
- energy / com. facility
- farms / forests / trees
- others

**Financial Loss**

- insured loss

**Figure 6.1a: Sample form - Wind Damage Database (thunderstorm event)**
<table>
<thead>
<tr>
<th>id</th>
<th>type of event</th>
<th>classification</th>
<th>tornadoes only</th>
</tr>
</thead>
<tbody>
<tr>
<td>121</td>
<td>tornado</td>
<td>F3</td>
<td>width (m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>length (km)</td>
</tr>
<tr>
<td>date</td>
<td>1983/11/24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>time</td>
<td>late afternoon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>map</td>
<td>min 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>hrs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>province</td>
<td>Natal</td>
<td>location</td>
<td>Mpendle near Impendle</td>
</tr>
<tr>
<td>longitude</td>
<td></td>
<td>latitude</td>
<td></td>
</tr>
</tbody>
</table>

**summary**

In the late afternoon a tornado struck the residential area of Mpendle near Impendle. Not one of the approximately 250 huts remained standing. 9 people were killed and 38 seriously injured. Hundreds of residents were searching for missing relatives. A car that was driven into the eye of the storm was flung 100 metres into the veld and the driver was killed. It was followed by a violent hailstorm. It sounded like a jumbo jet. Lasted 15 minutes. Looked like a big black snake that sucked all the clouds into a black column. Animals and poultry were lying dead all over the place. In one place there was a mass grave of about 150 cattle.

**notes**

- Cars were lifted off the ground (at least two of them were thrown a couple of hundred metres)
- The engine was ripped off the body of one car
- The remains of houses were scattered over a distance of about 10 km
- Corrugated iron wrapped around a tree
- The tornado started in the SSW and went to the east of Novuka

**references / witnesses**

Rand Daily Mail 1983/11/25
Beeld 1983/11/26
Daily News 1983/11/26
Natal Mercury 1983/11/28

---

Figure 6.1b: Sample form - Wind Damage Database (tornado event)
6.2 Assessment

As expected, the information which was obtained from the survey of the press and literature proved to be fairly fragmented and inconsistent. A substantial portion of press releases provide little quantitative data due to their descriptive and highly subjective media terminology, referring for example to a large number of people or hundreds of houses etc., and not the actual numbers.

Several of these reports were cross-referenced, re-analysed and upgraded where possible. The resulting database is included in the CD disc which forms a part of the current dissertation. Further analysis and enrichment of the data is possible (and would be beneficial) but this would form a substantial long-term (i.e. several years) project on its own, and was therefore not further investigated in this study.

6.3 Observations

The initial statistics of the wind-damage database are presented in Figures 6.2a to 6.2e. These were also presented at the International Workshop on Wind Disaster Reduction in Bochum (Goliger et al, 2000). The following can be noted in the figures.

- A trend is evident in which the number of wind-damage reports has increased since 1948 (Figure 6.2a). This could be attributed to the increase in population density (i.e. density of human development), better administrative and reporting procedures, as well as a possible climatic change.

![Figure 6.2a: Annual distribution of wind damage events](image)
The monthly distribution (Figure 6.2b) indicates that, contrary to common belief, most of the wind damage events occur in summer months (October through to February). These are mainly due to thunderstorms, downbursts, tornadoes and south-easterly coastal winds.

![Monthly distribution of damaging events](chart.png)

**Figure 6.2b: Monthly distribution of damaging events**

Injury and death due to windstorms seems to be on the increase (Figure 6.2c), particularly during the last few years (1400 people in the year 2000). About five devastating events affect the human population in a decade. The large number of injuries and deaths in the decade between 1950 and 1960 were due to two large tornadoes. The description of the events included in the database suggests that most of the loss of human life resulted from the direct failures of shelters (i.e. structures) and airborne debris originating from the structures.
Figure 6.2c: Life and limb consequences of strong wind events

- Figure 6.2d analyses the content of damage in respect of various types of structures. It can be seen that about 70% of reports included damage to houses and buildings, 30% to community structures and a similar percentage to power and communication systems.

Figure 6.2d: Reports of damage to various types of structures
• The information on damage to informal settlements is grossly underestimated due to poor communication and reporting systems which is compounded by the historically inadequate coverage by the media. This issue forms one of the major problem areas which is taken into account in the proposed risk model.

• This statement is supported by the analysis of the number of homeless people as a result of wind events included in Figure 6.2e. In recent years, with more attention being paid to underdeveloped communities, a significant increase in the number of homeless people is evident. This is largely attributed to better reporting on damage in areas of mass housing and informal developments.

![Figure 6.2e: Number of homeless people](image)

6.4 Relevance of the database

The database developed during the course of the current project captures a wealth of diverse information and motivates the need to develop the proposed risk model. The background data which is included, could be investigated further, cross-referenced and processed to determine additional characteristics and statistics of wind disasters in South Africa (for example the duration of devastating winds, or the consequent financial loss).

Further analyses (combined with a GIS system) would also provide a pool of useful information which would enable one to re-evaluate and upgrade the input data of the proposed risk model. This is in respect of the geographical prevalence of the occurrence of various types of strong wind events, the spatial extent of zones of strong wind events and the generic footprints of various type of events.
Chapter 7
7 PROPOSED RISK MODEL

7.1 Motivation

7.1.1 Design of structures vs. wind disaster

At first it may appear that the role, goals and status of wind structural design and wind disaster management are similar. However, for several reasons such an assumption is superficial, and this will be discussed below.

By definition, the ultimate goal of wind loading design of individual structures is focused on ensuring (on the basis of a conservative set of principles included in the relevant codification) that within an acceptable level of probability, the specific structure will be able to withstand the wind loads to which it is likely to be subjected during its lifetime. The wind loading design is the responsibility of a Structural Designer appointed by the Owner of a structure. The interest of the Owner is that the specific structure will survive the likely extreme wind loading but this interest does not extend to the neighbourhood of the structure.

Recent rapid improvements in structural testing, wind-tunnel modelling and information technology, has provided a platform that enables the development of new sets of much more accurate aerodynamic and structural response data on the loadings generated by the flow of wind over structures. Modern electronics and information technology also allow instantaneous and much more accurate handling of large sets of full-scale wind climatic data and the development of better, statistically based, predictive models of extreme winds. All these information and modelling tools can be harnessed to improve and optimise data on the design of individual structures.

The broad aims of wind disaster management are to predict, analyse and develop a relevant and adequate set of contingency plans to enable local and national authorities to deal with potential wind disasters affecting administrative or geographical regions within their area of responsibility. Within such a region (and especially in South Africa) only some structures would have some form of engineering and wind loading design inputs and construction supervision.

Unfortunately the direct application of current levels of sophistication and the results of modern scientific research on loading of structures to disaster management is much more
difficult. According to Prof Davenport (1995) this issue forms one of the missing links and remaining challenges of wind engineering science.

The links, common interests and differences in interests between the aims of wind loading design and wind disaster management can be summarised as follows:

- Within a region an assembly of individual amenities forms the built environment.

- Theoretically, if all of those amenities were designed to withstand critical loads, then the relevant codes and the design would be adequate and the amount of disaster would be limited to rational levels which should be acceptable to society.

- In the design codes the level of reliability is determined on a rational basis or is based on experience. Similarly, the proposed risk model provides a rational basis to relate and determine the level of acceptable risk of damage to all types of amenities.

- Designers and owners are responsible only for their individual structures.

- Disaster management authorities are interested in and responsible for the performance of all amenities within a region. This includes informal facilities.

- By definition the design of structures is based on an assumption of an extreme wind (within a specified probability of occurrence) affecting a specific structure in isolation. The magnitude of wind is based on the extreme value analysis of the available full-scale wind records and the assumption that these records are representative within the specified regions. All structures are significantly smaller (by several orders of magnitude) than the size of an administrative or geographic region and therefore there is no concern for the spatial extent of extreme wind events.

- From a disaster management point of view, the spatial extent and amount of damage due to disastrous events is one of the most critical factors affecting the total socio-economical impact.

- Because of the informal and low-cost component of the built environment in South Africa, a large portion of damage occurs at wind speeds substantially lower than
those stipulated by the design codes of practice, and such wind speeds occur more often than the extreme wind speeds relevant to the design of individual structures.

In conclusion, the aims of wind loading design of structures and wind disaster management are different. Disaster management takes account of:

- the large number of amenities which form the built-environment,
- a large spectrum of structures, and
- the spatial extent of damage,

due to strong winds with a larger number of occurrences (i.e. probability of occurrence) than the extreme winds relevant to the design of individual structures (i.e. subjected to once in their life-time.)

Furthermore, the prime concern of disaster management is the relationship between the magnitude of total loss and its probability of occurrence (i.e. return period). For example, from a forward planning point of view it is important to know whether to plan for events of limited extent and consequence and frequent occurrence or for disastrous events with a lower probability of occurrence.

7.1.2 Applicability of international research

The basic information on the wind loads generated on structures of specific geometric forms, as provided in the design codes of practice, is universal. However, for various reasons each country or geographical region can be characterised by its own construction principles, materials, technologies and development systems. (These reasons could roughly be grouped into: historical and traditional, climatologic and economic (including the availability of construction materials)).

The background research carried out in the course of the current study suggests that direct comparisons of the response of structures to wind loadings between various regions and countries could in some cases be unreasonable and may lead to large distortions of the true situation.

Other important and obvious differences between various geographic regions relate to climatic conditions. Each region has its own set of prevailing climatic parameters which in turn determine the characteristics of the dominant winds.
The above indicates that locally relevant, South African research into wind damage and disaster is critical.

The discussion in Chapter 3 indicates that over the years a fair amount of research has been done around the world in order to gain an understanding of the negative (destructive) impacts of wind action on human developments. This refers to the analysis of historical wind disaster events and subsequent damage, the development of relevant statistics, construction guidelines and design codification and finally prediction and risk models of the potential future damage.

Unfortunately very little such work has been done in South Africa. There is no overall picture or statistics of damage due to wind disasters and their consequences. Furthermore, there is no mechanism in place that would enable disaster management authorities to evaluate and predict the risks of future events and their consequences.

Clearly there is a gap in locally relevant (i.e. South African) knowledge. It is also evident that research directed at disaster management applications, and in particular the statistics of damage (reported in Chapter 6) and the risks of future wind damage, is needed. This is less necessary for the design purposes of individual structures where substantial components of international knowledge are readily available and applicable.

7.2 Risk of wind damage

The aim of the current Chapter is to develop a generic risk model of wind damage for disaster management purposes in South Africa.

The risk of wind damage at a particular point is related (among other things) to the probability of wind speeds of damaging magnitudes being exceeded at that point, and this philosophy has been adopted in international codification practice.

The basic design wind speeds for a geographic area are determined by an extreme value analysis of a measured time series at specific locations within that area, using one of the recognised tools for extreme value analysis. Acceptable levels of occurrence of extreme winds are then determined, and depending on the density of the recording stations, contour lines of wind speeds are developed. Some of the wind risk models presented in the literature are based on this principle, such as the model for potential cyclonic damage in Australia developed by Leicester et al (1979).
This approach assumes that any point within a geographic area of concern has the same probability as another point, to experience extreme winds. From a disaster management point of view, the shortcoming of this assumption is that it does not take into account the type and spatial extent of individual extreme events. Furthermore, as far as South African conditions are concerned, two other shortcomings are apparent:

- the poor distribution of reliable, long-term recording stations (16 cover an area of 1.2 millions km²), results in poor representativity of the data, and
- the assumption ignores climatic differences (i.e. differences in the characteristics of extreme wind events), which are significant.

Of particular relevance is the relatively poor spatial representation (applicability) of the recorded data. The map of the design wind speeds stipulated in the South African Loading Code SABS-0160 (Figure 5.2) was based on an extreme value analysis of long-term records from 14 Weather Bureau recording stations (Milford, 1987). The geographical distribution of these stations is presented in Figure 7.1. By comparison, similar maps for the Netherlands and UK were each developed using the data from more than 50 recording stations (Wieringa and Rijkkoort 1983; BRE Digest, 1989). A graphic comparison of the areas of three countries and the number of recording stations is given in Figures 7.2a and 7.2b. It can be seen that the differences are significant.

This issue becomes even more relevant when one considers the climatic diversity of South Africa in comparison with the above countries. The climates of the UK and Netherlands are fairly uniform and the strong wind events are generated, almost exclusively, by broad winter storm frontal systems. The climate in South Africa is much more complex and ranges from Subtropical (Natal) and Mediterranean (Cape) zones to Desert (Kalahari). The distribution of climatic zones in South Africa is presented in Figure 7.3 (Kruger, 2002).
Figure 7.1: Weather recording stations

Figure 7.2a: Comparison of areas

Figure 7.2b: Number of recording stations
7.3 Proposed approach

Another approach is to use the spatial extent of representative strong wind events (i.e. their footprints) and their average rate of occurrence within a specified geographic area (zone) to determine the probability of damaging winds per unit area. Such an approach has been used by McDonald (1983) in his analysis of the risk of tornadic strikes and more recently Drayton et al (1999) in their study of winter storms in Europe.

This approach is based on the principle that the amount of damage due to strong wind events is proportional to the area which is likely to be subject to certain ranges of wind speeds generated by those events. Based on first principles, and for a given geographic or administrative region, this in turn will be determined by the number of events per unit time (i.e. rate of occurrence) and their size and extent in the horizontal plane.

The initial investigation and discussions with experts at the South African Weather Bureau confirmed that, in view of the problems discussed in Section 7.2, this is the most relevant and suitable approach to the current project. This approach has therefore been adopted for the current study, which is based on the identification of the geographic zones of dominant types of strong winds in South Africa combined with the data on their occurrence and spatial extent.
Because of its generic nature, the proposed model tends to marginalise wind speeds of extreme magnitude, like those used in the design code of practice (i.e. with a 50 year return period). Such wind speeds are relevant for design purposes but to a lesser extent to disaster management. Furthermore, in author’s opinion, apart of the high intensity winds (like tornadoes and microbursts), a substantial proportion of the damage that occurs in South Africa is caused by wind speeds which are lower than those stipulated in the design codes.

The proposed model comprises several stages. Initially a generic algorithm is presented. This algorithm is based on the first principles of spatial statistics, in particular the risk of a specified range of wind speeds (originating in strong wind events) affecting a unit area within a certain geographic or administrative region. It takes into account the spatial distribution (extent) of strong winds within various types of wind events and their rate of occurrence per unit time (year). This information is then integrated with the data on the extent, asset value and strength of the amenities to estimate the total damage.

A flowchart of the proposed model is presented in Figure 7.4. Initially the area to be investigated has to be defined (block 1). (This would typically represent an administrative, commercial or industrial district of the country.) Subsequently the types of strong wind events to which the area of concern will be subject, is identified. This is done through the introduction of a useful concept of zones of strong wind events (block 2). The relevant wind related factors are then determined by defining the footprints (i.e. extent of areas subject to various ranges of wind speeds) for various types of strong wind events (block 3), and the rate of occurrence per unit time (block 4). All these components define the total extent of areas within the district of concern subjected to various ranges of wind speeds (block 6).

At this point human built development factors come into consideration. The total extent of human development (within the district of concern) will have to be established in terms of the distribution of assets at risk (block 5). A mutual relationship between the asset value and the vulnerability of amenities (represented by vulnerability curves) needs to be determined (blocks 7 and 8). (This refers to the fact that more costly amenities comprise better material and receive more engineering inputs during their design and construction.)

The extent of human built development, combined with the average asset value (block 9) and vulnerability curves (block 8), will determine the predicted loss due to strong wind events per unit time (block 10).
The proposed algorithm is presented in Section 7.4. In Chapters 8 and 9 three aspects of the model are discussed and developed, which form the South African wind-climatic inputs to the model are discussed and developed. These refer to the:

- identification of wind zones of occurrence of typical strong wind events in South Africa (block 2),
- development of the footprints of generic types of wind events (block 3), and
- development of the generic information on the rate of occurrence of various types of strong wind events (block 4).

Figure 7.4: Schematic flowchart of the model
7.4 Mathematical procedure

7.4.1 Areas subjected to ranges of wind speeds

Consider a geographical (or administrative) region with an area A (Region A), extending within a wind-zone characterised by the occurrence of one type of strong wind only, and assume that:

- the Region A is climatologically homogeneous, and therefore, the spatial likelihood of the occurrence of a strong event is uniform,
- the Region A is, in statistical terms, significantly larger than the area a of an individual wind event (A«a),
- the probability of two subsequent wind events affecting the same place within the region in one year is negligible, and
- the extent of all the likely wind events falls within Region A.

Now consider an individual type of strong wind event W, with a generic footprint as presented in Figure 7.5. Within this footprint the area:

- a1 is defined as an area with a peak wind speed greater than or equal to V1, (i.e. v≥V1) and,
- a1 is an area with a peak wind speed greater than or equal to Vi (i.e. v≥Vi).

![Figure 7.5: Generic footprint of a strong wind event type W, over a Region A](image)

Area a1 is defined as:

\[ a_1 = w_1 \cdot l_1 \]
Let \( N \) be the average number of strong wind events type \( W \) per year which occur within the Region A.

The total area within Region A that will be exposed to wind speeds greater than or equal to the threshold wind speed \( v_i \) in a year can be expressed as:

\[
\sum a_i (v \geq v_i) = N \cdot a_i
\]  

[2]

The relationship between the total area and wind speed threshold can then be presented schematically as in Figure 7.6. (The assumed trend in the relationships, i.e. larger areas corresponding to lower magnitude wind speeds reflects the expected spatial trend.)

![Figure 7.6: Areas subject to ranges of wind speeds](image)

The rate of occurrence per unit area within Region A, of a wind speed greater than or equal to the threshold \( v_i \) can be expressed as:

\[
R(v \geq v_i) = \frac{N \cdot a_i}{A}
\]

[3]

### 7.4.2 Developed areas subjected to ranges of wind speeds

The relationship between the rate of occurrence of the range of wind speeds per kilometre square can then be plotted as shown in Figure 7.7.
The extent of damage in Region A will depend on the distribution of human developments and/or settlements (s) with homogeneous asset distribution subject to the wind speeds generated by wind events type W. Now assume that Region A contains n number of settlements, with areas $s_1$, $s_2$, $s_i$, $s_n$ as presented in Figure 7.8.

The total exposure area (i.e. number of kilometres square) of developed land in Region A subjected to wind speed $v_i$ per year can be expressed as:
\[
\sum s(v \geq v_i) = N \cdot a_i \cdot \frac{1}{A} \sum_{j=1}^{n} s_j
\]  \[4\]

The rate of occurrence of a wind speed with a threshold value \( v_i \) affecting a unit area of a developed settlements \( s_i \) within Region A can then be expressed as:

\[
R(v \geq v_i) = \frac{N \cdot a_i}{A} \frac{1}{A} \sum_{j=1}^{n} s_j
\]  \[5\]

On the basis of the above equations, two graphs can be developed as are presented schematically in Figures 7.9 and 7.10. Figure 7.9 relates to the total developed area exposed to various ranges of wind speeds and Figure 7.10 correlates the rate of occurrence of a developed unit area within region A, being subjected to different wind speeds.

![Figure 7.9: Developed areas subject to ranges of wind speeds](image-url)
7.4.3 Development densities and asset values subject to ranges of wind speeds

In reality the density of population, human built development and distribution of assets is not uniform. For a typical suburban and urban settlement, density increases towards the centre and such a generic situation is presented schematically in Figure 7.11a. In this sketch a settlement $s_j$ contains densities of development and assets $d_1, d_2, ... d_k$.

If the area $s_j(d_k)$ is defined as an area with an average asset density $d_k$ within settlement $s_j$, the total extent of the development with various density levels of assets can then be expressed as the sum of the respective densities in various settlements i.e.: 
\[ \sum_{j=1}^{n} s_j(d_k) = s_1(d_k) + s_2(d_k) + ... + s_n(d_k) \]  

and the ratios

\[ \sum_{j=1}^{n} \frac{s_j(d_1)}{A} \sum_{j=1}^{n} \frac{s_j(d_2)}{A} \cdots \sum_{j=1}^{n} \frac{s_j(d_k)}{A} \]

represent the fractions of the total area of Region A that have development densities of \( d_1 \), \( d_2 \), ..., \( d_k \).

The total settlement area with a specific development density \( d_k \) affected by a specific wind magnitude \( v_i \) will be:

\[ \sum \frac{s_{d_k}(v \geq v_i)}{A} = N \cdot a_i \cdot \frac{1}{A} \cdot \sum_{j=1}^{n} s_j(d_k) \]  

The rate of occurrence for all areas within Region A with a specific development density of \( d_k \) being exposed to a wind speed with a specific magnitude of \( v_i \) will then be defined as:

\[ R_{d_k}(v \geq v_i) = \frac{N \cdot a_i}{A} \cdot \frac{1}{A} \cdot \sum_{j=1}^{n} s_j(d_k) \]  

It is then possible to plot the functions relating the exposed area and threshold wind speed for each density of human development as was done in Figure 7.9 and for rate of occurrence as in Figure 7.10.

Apart from loss of human life, the most important information for disaster management purposes is the economic impact of the accumulated wind damage. Information on the extent of human built development \( d_k \) per unit area, therefore, has to be converted to monetary terms to determine the average value of assets per \( m_k \) per unit area. For this one should consider the average number and type of structures and their average value.

In general, and even more so in South Africa, the distribution of human built development and population density do not coincide with the distribution of wealth and average asset values. For example a densely populated informal township may represent a low asset monetary value in comparison with a large industrial, commercial complex or an office block,
which have a very low population density. The distribution of asset values does not necessarily follow any prescribed pattern and is largely determined by geo-economical factors like availability of land or transportation routes. Such a situation is presented schematically in Figure 7.11b in which \( m_1, m_2, \ldots, m_k \) refer to various levels of average asset values.

![Figure 7.11b: Distribution of asset values in settlement \( s_j \)](image)

A similar methodology to that presented in equations [1] to [9], can be applied to the distribution of assets, in which the area \( s_i(m_k) \) can be defined as an area with an average asset value \( m_k \) within settlement \( s_i \), and the total extent of the development with various density levels of assets can then be expressed as the sum of the respective densities in various settlements i.e.:

\[
\sum_{j=1}^{n} s_j(m_k) = s_1(m_k) + s_2(m_k) + \ldots + s_n(m_k)
\]

and the ratios

\[
\frac{\sum_{j=1}^{n} s_j(m_1)}{A} : \frac{\sum_{j=1}^{n} s_j(m_2)}{A} : \ldots : \frac{\sum_{j=1}^{n} s_j(m_k)}{A}
\]

represent the fractions of the total area of Region A that have average asset values of \( m_1, m_2, \ldots, m_k \).
Similarly, the equations [8] and [9] can be re-written in a form in which the total settlement area with a specific asset value \( m_k \) affected by a specific wind magnitude \( v_i \) will be:

\[
\sum s_{mk}(v \geq v_i) = N \cdot a_i \cdot \frac{1}{A} \cdot \sum_{j=1}^{n} s_j(m_k)
\]  

[12]

and the rate of occurrence for all areas within Region A with a specific asset value \( m_k \) being exposed to a wind speed with a specific magnitude of \( v_i \) will then be defined as:

\[
R_{mk}(v \geq v_i) = \frac{N \cdot a_i}{A} \cdot \frac{1}{A} \cdot \sum_{j=1}^{n} s_j(m_k)
\]

[13]

7.4.4 Accumulated economic loss

Based on equation [12] the relationship between the areas of various ranges of asset values and the magnitude of wind speed to which these areas will be subjected can be derived as presented schematically in Figure 7.12. In this figure it is assumed that larger areas correspond to lower asset values. Such an assumption may not necessarily be true for urbanised regions and this will in fact be the case in Section 11.1, in which a worked example of the model will be demonstrated.

![Figure 7.12: Total area for each development asset value exposed to threshold levels of wind speed](image-url)
Figure 7.12 illustrates that:

- for a density development equivalent to an average value of assets of \( m_2 \),
- an area of \( a(m_2) \),
- will be subject to the threshold wind speed of \( v_2 \).

The resultant damage will depend on the value of the assets at risk and also the wind resistance of the structures. The relationship between wind speed and consequent damage is typically referred to as the vulnerability function (discussed in Section 3.4.2.2) and can be expressed in terms of a vulnerability index \( t_i(m_k) \) which is defined as a ratio of the average value of damage corresponding to a specific asset value, as a result of exposure to a specific range of wind speeds \( D(m_k,v_i) \) and the initial asset value \( m_k \) namely:

\[
t_i(m_k) = \frac{D(m_k,v_i)}{m_k}
\]  

The vulnerability of a structure depends largely on its type (e.g. high- versus low-rise structure) and cost, which in South African conditions can typically be linked to the amount of engineering input. For the current model (and in the absence of any relevant data) an assumption is proposed in which the vulnerability function is proportional to the wealth of the area and therefore its asset value. A schematic graph including three vulnerability curves is presented in Figure 7.13. This graph implies that the assets in the area with average asset value \( m_k \) is less vulnerable to wind damage or disaster than the area with average asset value \( m_1 \).

![Figure 7.13: Generic vulnerability curves](image-url)
From equation [14] the expected damage cost per unit area for various asset values $D_{(mk,vi)}$ exposed to ranges of wind speeds can be derived as:

$$D_{(mk,vi)} = t_i(m_k) \cdot m_k$$  \[15\]

By multiplying the expected cost of damage per unit area (equation [15]) by the total settlement area with a specific asset value $m_k$ exposed to a specific wind magnitude $v_i$ (equation [12]), the total loss for a specific asset value and wind speed magnitude can be expressed as:

$$L_{(mk,vi)} = D_{(mk,vi)} \cdot \sum s_{mk} (v \geq v_i)$$  \[16\]

The total loss within the areas of a specific asset value and due to all ranges of wind speed can be expressed as:

$$L_{(mk)} = \sum_i L_{(mk,vi)}$$  \[17\]

and the expected average loss $L_{(A,W)}$ per year for Region A, due to wind event type $W$, can be expressed as:

$$L_{(A,W)} = \sum_k \sum_i L_{(mk,vi)}$$  \[18\]

7.4.5 Other considerations

7.4.5.1 Combination of various types of wind events
Where different types of wind events ($W_p$) affect Region A, a similar procedure would have to be implemented to account for damage due to other types of strong winds. The total loss in Region A can then be expressed as:

$$L_{(A)} = \sum_p L_{(A,W_p)}$$  \[19\]

where $p$ is the number of types of strong wind events $W$ to which Region A may be exposed.
7.4.5.2 Climatic non-homogeneity of a district of concern

Where Region A constitutes a large administrative region which is not homogenous as far as the occurrence of different types of strong wind event is concerned, the calculation becomes more complex. One would have to subdivide the region into homogenous sub-regions, and make individual calculations for each sub-region. The total loss would then be the sum of the losses in each of the sub-regions.

7.5 Information required

The application of the model requires information on a large number of variables. These can roughly be grouped into three categories, as highlighted in Figure 7.14. The variables related to wind action (blocks 2, 3 and 4) are analysed and developed in Chapters 8 and 9.

A discussion on the available data on human built development in South Africa (blocks 1 and 5) is presented in Chapter 10. There is a need for information on the distribution of assets (block 7) and vulnerability of amenities (block 8).

Being beyond the scope of the current study, these aspects were not investigated although some assumptions are made in Chapter 11 for purposes of practical demonstration of the proposed model.
Figure 7.14: Diagram of the process
Chapter 8
8 IDENTIFICATION OF ZONES OF STRONG WIND EVENTS

8.1 Process and general comments

In this chapter the division of South Africa into zones of strong wind events is proposed.

The approach taken was to develop a first approximation division based on the limited information from relevant literature and by accessing, extracting, analysing and interpreting the available information.

The development process consisted of a series of informal workshops and discussions involving selected experts at the SA Weather Bureau, that were organised, facilitated and documented by the author of the current dissertation. These were attended by Messrs:

- Andries Kruger: First Meteorologist, Directorate Climatology (responsible for the development of the WB official publication on surface winds),
- Ian Hunter, Deputy Director: Marine Meteorological Services, and
- Frank Adam: Specialist Scientist, Directorate Research (expert on severe weather).

The workshops were followed by a supplementary literature survey and discussions. Additional input and review was also provided by Ms E de Coning (Directorate Research).

The development process of identifying zones of strong winds was aimed at identifying the dominant types of winds for each zone and did not exclude overlapping between zones (Goliger and Retief, 2001). Furthermore, the process was aimed at those wind characteristics which affect the lowest regions of the boundary layer (i.e. the built environment), rather than the climatological origin and upper level mechanisms of the air mass movement.

The process was aimed at best estimates rather than conservative estimates of all elements of the model. This was done to avoid unnecessary accumulation of conservatism, in which the information gathered from the public domain has a tendency for overestimation, and which needs to be compensated for.

After the initial analysis of the types of strong winds, their origin and geographic occurrence, it was decided to ignore the effects of tropical cyclonic winds.
Because of the steep pressure gradient (Hunter, 2001) the southern portions of tropical cyclones, which occur off the northern coast of KwaZulu-Natal, can develop extreme wind speeds affecting the southern portion of Madagascar and the Mozambique coast; however, further inland they tend to dissipate rapidly, before reaching South Africa. Similar characteristics of cyclonic winds (i.e. their rapid dissipation over a land-mass) have been noted by Somayaji et al, (1995). (Note that this does not apply, however, to the accompanying rainfall.)

8.2 Inland and coastal winds

Two distinct types of strong winds were identified namely inland and coastal or frontal.

Strong inland winds originate typically as a result of severe convective activity, in which a significant upward movement is caused by hot air, which rises, cools, saturates and forms a cumulus cloud. The cloud grows vertically into a thunderstorm cell, with strong wind outflows at ground level. The thunderstorms can also produce other types of extreme wind events such as tornadoes and downbursts or microbursts.

Coastal winds are due to frontal low-pressure systems. These may occasionally be accompanied by convective activities and in extreme cases can also produce tornadoes (Cape Flats, 29 August 1999 or Saldanha Bay, 12 September 1987). The development of cool-season tornadoes has also been reported in Europe, Australia and the USA (Goliger and Milford, 1998).

8.3 Zones of strong wind events

Three zones of Inland Winds (Zones 1 to 3) and four zones of Coastal Winds (Zones 4 to 7) have been identified (Goliger, 2000/2001; De Conning, 2001).

The extent of Zone 1 and Zone 2 (and to a lesser extent Zone 3) was derived from an interpretation of the data-sheet on yearly distribution of recorded thunderstorm flashes in South Africa (Geldenhuys, year unknown) and the Weather Bureau publication (Schultze, 1965). Zones with larger numbers of thunderstorms are expected to experience a greater occurrence of more severe events. The number of days with thunder was therefore selected for the basis of classification for the inland zones.
The extent of Zones 4 to 7 was established on the basis of the inputs of experts listed in Section 8.1 and also the research of Hunter (1986).

The distribution of the proposed zones is presented in Figure 8.1 and a brief description of each follows. This distribution relates to the classification of the severe storms discussed in Section 5.1.

zones of inland winds  
(occur in summer, spring, autumn)

zones of coastal and frontal winds  
(area: 875 000 km$^2$)
weak and moderate thunderstorms  
20<n<50 days with thunder

(area: 390 000 km$^2$)
strong thunderstorms  
50<n<80 days with thunder

(area: 225 000 km$^2$)
intense thunderstorms/tornadoes/ downbursts

zones of coastal and frontal winds  

(area: 50 000 km$^2$)
coastal low buster  
(occur entire year)

(area: 120 000 km$^2$)
cut-off-lows - westerly & easterly  
(occur in spring and autumn)

(area: 60 000 km$^2$)
shallow south-easter  
(occur in summer)

(area: 480 000 km$^2$)
mid-latitude lows  
(occur in winter)

Figure 8.1: Zones of strong wind events in South Africa
8.3.1 Zone 1: weak to moderate thunderstorms

This zone is characterised by an average of 20 to 50 days with thunder per year. It extends over almost the entire country but excludes parts of the Western and Northern Cape. The area of Zone 1 is 875,000 km\(^2\).

8.3.2 Zone 2: weak, moderate and strong thunderstorms

In this zone thunder occurs on average on 50 to 80 days per year. The zone extends over several provinces of the central and northern part of the country (i.e. Free State, North-West Province, Gauteng, Mpumalanga and KwaZulu-Natal). The zone is 390,000 km\(^2\) in extent.

8.3.3 Zone 3: weak, moderate, strong and intense thunderstorms

Zone 3 experiences all types of thunderstorms including intense ones (i.e. super-cells and squall-lines), which also are known to produce tornadoes and downbursts. These high intensity wind events develop when the intense thunderstorms transform to an organised structure of sufficient strength (Goliger et al 1997). Although the geographical extent of downburst and tornadoes is very small in relation to the intense thunderstorms, they can generate extreme winds in excess of 50 m/s. These events are typically responsible for significant damage to structures.

Zone 3 is 225,000 km\(^2\) in extent and extends mainly over KwaZulu-Natal, Mpumalanga and over parts of the Free State, Gauteng and Eastern Cape.

8.3.4 Zone 4: coastal low - busters

Zone 4 experiences coastal low – busters and extends along the KwaZulu-Natal and Eastern Cape coast between Algoa Bay (west of East London) and the Mozambican Channel. The zone is about 850 kilometres long and is assumed to cover 50,000 km\(^2\).

8.3.5 Zone 5: cut-off lows - easterly and westerly

The cut-off lows develop in extra-tropical cyclones. The zone covers the coastal areas of the Eastern and Western Cape, and is 120,000 km\(^2\) in extent. (In the south-western Cape the cut-off lows are influenced by the dominant topography.)
8.3.6 Zone 6: coastal low – shallow south-easter

Shallow south-easterly trade winds develop as a result of localised coastal lows and their influence extends along the western and southern coast of South Africa, from Luderitz to Mossel Bay. It is 60 000 km\(^2\) in extent. Because of their low depth (about one km) they can be influenced by topography. In Namibia a marked influence of the afternoon sea breeze is evident.

8.3.7 Zone 7: mid-latitude low

The mid-latitude large-scale low circulation systems develop over the southern oceans dominated by the Antarctic Circumpolar current. They can affect the coastal areas between the Port Nolloth (on the Namibian border) and East London. (A typical example of a mid-latitude low is that which caused devastation in Cape Town in 16 May 1984.)

Inland they can extend up to 1000 km from the southern coastline as far as Upington and Kimberley. The zone covers more than 1/3 of the area of the country, mainly over the Western, Eastern and Northern Cape and southern portion of the Free-State. The area of the zone is taken as 480 000 km\(^2\).

8.4 Occurrence of wind events, overlaps and anomalies

Mapping of the zones provides a practical and useful first approximation of the relevant properties of the highly complex climatic characteristics of South Africa. However, even this simplified and practical description of surface wind zones introduces some complications.

For example consider Figure 8.2a in which the layouts of Zones 1-3 have been overlaid. It can be seen that although from the geographic extent point of view Zone 1 covers the whole of Zones 2 and 3, only a portion of Zone 1 (area I) overlays all three zones. This portion also includes the most populated and industrialised part of South Africa. This implies that an administrative district within that part of the country will be subject to the occurrence of all types of winds due to convective activity namely: weak and moderate, strong and intense thunderstorms, as well as downbursts and tornadoes.

Some other inland regions of the country in areas subject to convective activity will only experience weak and moderate thunderstorms (area III). In these regions (which typically
coincide with the Northern Cape) very little thunderstorm related wind damage is ever reported. These regions are also characterised by a very low population density.

Figure 8.2: Overlaps between the zones of strong wind occurrence

Certain areas of the country, in particular the western portion of Zone 2 (area II), will be subject to the occurrence of weak, moderate and strong thunderstorms, but not intense events. It is interesting to note that this also includes Welkom and its surroundings, where
several tornado events (related to intense thunderstorm activity) have been recorded in the last 30 years. This geographic inconsistency or anomaly became evident during computer modelling of the distribution of the mean rate of occurrence of tornado events in South Africa (Goliger et al 1997).

Another interesting anomaly is raised when considering Figure 8.2b. It can be seen that a coastal strip of land along the KwaZulu-Natal coast (area IV) will only be subject to weak, moderate and intense thunderstorms but not to strong thunderstorms. This is due to the occurrence of intense, and fast travelling thunderstorms along that stretch of the coast. In contrast with mature thunderstorm cells and squall-lines, these thunderstorms are characterised by a relatively small spatial extent in the horizontal plane but a well developed and high vertical structure and can generate severe downdrafts, downbursts and tornadoes. Many of these events affect rural KwaZulu-Natal and go unreported. A recently reported thunderstorm in March 2002, resulted in damage to a large commercial complex in Umhlanga Rocks north of Durban.

In Figure 8.2c all coastal / frontal zones of strong wind events are overlaid. It can be seen that the southern portion of South Africa (more than $\frac{1}{3}$ of the total area of the country) is dominated by the occurrence of winds due to winter mid-latitude lows (area V). (This accounts for the common opinion regarding the origin of dominant winds and damage in South Africa, which was raised in Section 6.4.)

Elsewhere along the northern coastlines (both eastern and western) in areas VI and VII zones of coastal low busters and shallow south-easters are evident, but they only penetrate about 50 kilometres, and therefore the affected areas are relatively small.

In summary, due to the very complex climate of South Africa, drastic simplifications to characterise the properties of surface winds in various geographic regions, were made. The overlapping of various zones provides a useful insight into the implications of the division which has been adopted. This topic can be fruitfully explored in future research studies.

The implications of the levels of uncertainty in defining the zones of occurrence of dominant types of wind events will be taken into account in the reliability analysis of the model.
Chapter 9
9 DEVELOPMENT OF GENERIC FOOTPRINTS AND OCCURRENCE RATE

9.1 Background discussion on wind speed footprints of wind events

From a disaster management point of view, one of the most important parameters affecting the overall amount of damage is the spatial extent of the extreme wind event(s). In the horizontal plane (i.e. that affecting the ground level and built environment), this can be referred to as the footprint of the event(s), as indicated in block 3, Figure 7.4.

Although each individual event develops its own unique footprint, it is possible to identify a typical one for each type of windstorm. Such a typical footprint could be developed statistically either on the basis of photogrammetric measurements of the actual damage due to various types of events, or more generically on the basis of their climatological characteristics.

For certain types of events and specific geographic regions, information on generic footprints has been developed and/or published. In particular one can refer to:

- The matrix of generic footprints of American tornadoes developed by McDonald (1983). This model has also been applied to the analysis of South African tornado events (Goliger et al. 1997).

- The footprint of a generic downburst proposed by Holmes (1999).


No research on this has ever been done in South Africa, and the process presented in this chapter attempts to solve the problem of the lack of relevant statistical information.

It has to be noted that although the information is of a fairly generic (therefore approximate) nature, the wind speeds quoted in the following sub-sections refer, in principle, to the peak gust wind speeds at the standard meteorological elevation of 10 metres above ground level in open terrain. Furthermore, due to the nature of the entire project, the data on wind
speeds refers to typical ranges of strong / damaging wind speeds rather than wind speeds of extreme magnitude and very low probability of occurrence (e.g. 50 year return period, as stipulated in the design codes).

9.2 Thunderstorms (Zones 1–3)

9.2.1 Proposed methodology

A review of wind engineering literature and follow-up discussions carried out in the course of the current project, indicate that no recognised information on the spatial extent and distribution of wind speeds within thunderstorms, and in particular for South African thunderstorms, is available. Contacts with meteorologists at the SA Weather Bureau revealed however that a fairly well established and acknowledged method of categorising thunderstorm events is widely used within the meteorological profession.

In particular, three generic types of thunderstorms outlined in Chapter 8 and defined as weak / moderate, strong and intense are identified and their typical layouts are stipulated by the Lemon Technique (2000) as presented in Figure 9.1. These layouts have been developed from weather radar data, using so-called reflectivity images.

Reflectivity images of thunderstorms can be obtained from weather-radar which transmit the electro-magnetic waves and detect water droplets of diameters exceeding approximately 1 mm. The water droplets contained within the radar sample volume reflect the power of pulse, which can be measured. The larger the diameter of the droplets and the more numerous, the higher the reflected power from the droplets back to the radar antenna. The returned power is related to a radar reflectivity value, namely dBZ, which is a logarithmus derived value from the returned power of the droplets sampled. An example of a reflectivity image of a thunderstorm is presented in Figure 9.2.
Figure 9.1: Radar reflectivity layouts of thunderstorms: a) weak to moderate, b) strong and c) intense
The experience of the Adam (2000/2001), gained during several years of research at the Bethlehem Precipitation Research Project of the Weather Bureau suggests that in weak, moderate and strong thunderstorms the highest wind speeds at ground level occur in the regions close to the rain-shaft which forms the centre of thunderstorms. (This does not refer to the strong winds that precede thunderstorms, the so-called leader gusts.)

Follow-up discussions with the Dutch Weather Institute (Wessels, 2002) confirmed this opinion in which a correlation between a strong radar-echo (i.e. high probability of strong instability) and the presence of strong horizontal winds is apparent.

From a numeric modelling point of view (Hand, 2000), convective gust wind speed can be broken down into three terms, namely: buoyancy, water loading and kinetic energy. (The
convective contribution to wind gust is based on the work of Nakamura et al, 1996.) Wind gusts in thunderstorms can, therefore, be related to changes in radar reflectivity patterns with time. (This is because radar reflectivity is a function of the size and concentration of hydrometeors which can be linked to water buoyancy, water loading and kinetic energy.)

Based on the above, an attempt was made in the current study to further investigate the correlation between measured reflectivity and wind speed, and by doing so, the feasibility of adopting typical layouts based on reflectivity images as generic footprints of wind speed distribution within thunderstorms.

*It is appreciated that radar reflectivity observations are only indirectly related to wind speed. However, the well documented physical measurement of reflectivity provides useful quantitative data through a correlation model on wind speed, for which little information is available.*

### 9.2.2 Peak wind speed and reflectivity

The investigation involved searching the reflectivity images contained in the radar archives of the Weather Bureau and selecting suitable and reliable records where the thunderstorm (including its core) crossed directly over an operational and reliable wind speed recording gauge.

The process of searching the archives, selecting, accessing and extracting the records proved to be very time consuming. As limited resources were available for the project, the research was eventually limited to initial comparisons of a pilot nature.

Figures 9.3a and 9.3b are examples of two time series of the recorded peak gust wind speeds (maxima within five minute intervals) and the reflectivity at an elevation 3 km above the recording anemometer.
Figure 9.3: Comparison of wind speeds and radar reflectivity: 
a) Bethlehem, 28 November 1995, b) Bloemfontein, 4 November 2000

Several data points obtained from five thunderstorm records (which, apart from the above, 
also includes Bethlehem 29 December 1997, Irene, 21 October 1999 and Bloemfontein 03 
November 1999) of peak wind speed and the corresponding reflectivity were extracted and 
compared in Figure 9.4 in a format similar to regression analysis. The horizontal axis 
corresponds to the peak wind speed and the vertical to the reflectivity level (dBZ) measured 
at the same instant of time. Although a fair amount of scatter is present, a rough relationship 
in which the dBZ reading is larger, more or less twice that of the peak wind speed (in m/s), 
can be noted and such a relationship has been assumed for the purpose of the current 
study. It can also be noted that for higher values of wind speeds, which are of relevance to 
the current project, a ratio 2:1 appears to be reasonable.
Figure 9.4: Comparison of reflectivity index and gust wind speeds

9.2.3 Generic footprints of wind speeds

Based on the above assumption, three generic 'point-in-time' layouts of wind speed distribution within thunderstorm events (similar to those stipulated in the Lemon Technique) were adopted for further analysis as presented in Figure 9.5.

Thunderstorms are not stationary and as a result of their horizontal movement, the areas subjected to strong winds are much larger than those indicated by the Lemon Technique. The extent of these areas depends on the duration and travel speed of thunderstorms as is presented schematically in Figure 9.6, for weak / moderate thunderstorms. Typical parameters of thunderstorm travel used by South African meteorologists are:

- ½ hour duration, 20 km per hour travel speed and 10 km travel distance, for the air-mass (i.e. weak and moderate thunderstorms), and
- 1 hour duration, 25 to 30 km per hour travel speed and 25-30 km travel distance for strong thunderstorms.

No such information is available for intense thunderstorms but a 2-hour duration period, 30 km per hour travel speed and 60 km travel distance are suggested.
Figure 9.5: Generic footprints of wind speeds in thunderstorm: a) weak to moderate, b) strong and c) intense

On the basis of the above information, the matrices for the generic footprints of typical thunderstorms have been derived as presented in Table 9.1. Note that in these matrices areas subject to wind speeds of less than 15 m/s are ignored (as they are less relevant to
the current project) and also that the descriptor 'weak' refers to weak and moderate thunderstorms as defined in the Lemon Technique.

Table 9.1: Matrices of width ($W_{ki}$) and length ($l_{ki}$), (km) in terms of wind speeds and storm classification

<table>
<thead>
<tr>
<th>velocity (m/s) ▶</th>
<th>storm ▼</th>
<th>&gt;15</th>
<th>&gt;20</th>
<th>&gt;25</th>
</tr>
</thead>
<tbody>
<tr>
<td>weak (k=1)</td>
<td></td>
<td>$W_{11}=10$</td>
<td>$W_{12}=5$</td>
<td>-</td>
</tr>
<tr>
<td>strong (k=2)</td>
<td></td>
<td>$W_{21}=12.5$</td>
<td>$W_{22}=7.5$</td>
<td>$W_{23}=2$</td>
</tr>
<tr>
<td>intense (k=3)</td>
<td></td>
<td>$W_{31}=17.5$</td>
<td>$W_{32}=10$</td>
<td>$W_{33}=5$</td>
</tr>
<tr>
<td></td>
<td>$i = 1$</td>
<td>$i = 3$</td>
<td>$i = 3$</td>
<td>$i = 3$</td>
</tr>
<tr>
<td>weak (k=1)</td>
<td></td>
<td>$l_{11}=20$</td>
<td>$l_{12}=10$</td>
<td>-</td>
</tr>
<tr>
<td>strong (k=2)</td>
<td></td>
<td>$l_{21}=35$</td>
<td>$l_{22}=25$</td>
<td>$l_{23}=15$</td>
</tr>
<tr>
<td>intense (k=3)</td>
<td></td>
<td>$l_{31}=100$</td>
<td>$l_{32}=70$</td>
<td>$l_{33}=20$</td>
</tr>
</tbody>
</table>

Due to the approximate nature of the above information, the following generic areas presented in Table 9.2 were adopted in the current study.

Table 9.2: Matrix of generic areas (footprints) (km$^2$) in terms of wind speeds and storm classification

<table>
<thead>
<tr>
<th>velocity (m/s) ▶</th>
<th>storm ▼</th>
<th>&gt;15</th>
<th>&gt;20</th>
<th>&gt;25</th>
</tr>
</thead>
<tbody>
<tr>
<td>weak (k=1)</td>
<td></td>
<td>$a_{11}=200$</td>
<td>$a_{12}=50$</td>
<td>-</td>
</tr>
<tr>
<td>strong (k=2)</td>
<td></td>
<td>$a_{21}=500$</td>
<td>$a_{22}=200$</td>
<td>$a_{23}=50$</td>
</tr>
<tr>
<td>intense (k=3)</td>
<td></td>
<td>$a_{31}=2000$</td>
<td>$a_{32}=500$</td>
<td>$a_{33}=200$</td>
</tr>
</tbody>
</table>

To recap, the current model assumes that, depending on the specific geographic locality:

- weak and moderate thunderstorms can occur in Zones 1, 2 and 3,
- strong thunderstorms can develop over Zones 2 and 3, and
- intense thunderstorms (as well as tornadoes and downbursts) can only develop in Zone 3.

This means that a specific area of concern (say an administrative district) and, depending on the extent and overlap of the various zones, can experience various convective wind events. For example within the geographic region presented in Figure 8.2a, in which Zones 1-3 overlap, all the types of strong winds due to convective activity can occur, but this is not the case for the coastal stretch of land presented in Figure 8.2b, which may experience weak, moderate and intense thunderstorms, downbursts and tornadoes, but not strong thunderstorms.
9.3 Extreme wind events: tornadoes and downbursts (Zone 3)

It is assumed that tornadoes and downbursts originate in intense thunderstorms and that they only occur in Zone 3. The spatial extent of high magnitude winds is very small in comparison with thunderstorms.

The generic footprint of a downburst proposed by Holmes (1999) is presented in Figure 9.7. This figure also includes a table of approximate areas subject to ranges of wind speeds, which was derived from the footprint. The extent of the generic footprints of tornadoes depends on their type (size) and have been researched by Fujita (1973) and McDonald.
(1983). The occurrence and characteristics of South African tornadoes was discussed in detail in Goliger et al (1997), and will not be discussed in the present dissertation.

The above information on footprints will be used in Chapter 11 in which the application of the model will be demonstrated.

![Figure 9.7: Footprint of a downburst](image)

### 9.4 Frontal / coastal winds (Zones 4-7)

Based on the macro-climatic characteristics of the coastal / frontal weather systems, it is assumed that the generic footprints of individual events envelop entire zones i.e. coincide with the spatial extent of the respective zones.

Apart from the general ranges of wind speeds which are given below, it is not possible at this stage, to identify / derive representative information on the spatial distribution / footprints of strong winds within the frontal / coastal wind systems. These distributions are influenced by the prominent topography along the southern coastal regions of South Africa. Development of such information can be based on the extent of various zones, areas of overlaps, and the experience of the Weather Service. This could be supplemented by climatic information on the vertical structure of frontal events, the effects of topography and limited full-scale records from the main developed areas (e.g. Cape Town, Durban or Port Elizabeth).

**Zone 4: coastal low - busters**

The width of individual events in Zone 4 is about 700-800 km and the inland penetration about 50 – 60 km. Coastal busters usually extend over the entire area of the zone. Two types of busters can be identified, namely:

- less severe, generating strong winds of up to 20 m/s, and
- more severe, with wind speeds up to 30 m/s.
Zone 5: cut-off lows easterly and westerly
The footprint of an individual system is typically between 300 and 400 km and inland penetration about 100 km. Typical wind speeds are between 20 and 30 m/s.

Zone 6: coastal low-shallow south easters
The spatial extent of an individual event is about 500 km along the coast and inland penetration about 50 km. The range of extreme wind speeds is typically between 20 and 30 m/s.

Zone 7: mid-latitude low
Typically, individual events envelop the entire zone, and their average footprints are assumed to be about 700 x 700 km. Peak wind speeds are associated with the frontal passage, typically between 20 and 35 m/s, although wind speeds in excess of 40 m/s have been recorded.

9.5 Occurrence rates

9.5.1 Thunderstorms (Zones 1-3)

Three zones of thunderstorm events (k=1 to 3) were identified for the current investigation. In the present investigation, information on the average number of thunderstorm occurrences in zones 1 to 3 was developed on the basis of interpreting and extrapolating the results of the analysis of more than three thousand events recorded at the Bethlehem Weather Bureau Station (Steyn and Bruinjes 1990). The distribution of these events in terms of their lifetime is presented in Figure 9.9.

This was done by considering the coverage area of the Bethlehem radar (44 000 km²) and assuming that the weak, moderate, strong and severe thunderstorm events that occurred in this area, are representative for Zones 1 to 3, (i.e. the monthly variance from west to east was ignored).

The process of developing the information for the purpose of the current project is summarised below.
Zone 1
- Assume the life cycle of a typical air-mass thunderstorm is up to ½ hour.
- It can be derived from Figure 9.9 that this corresponds to 62% of events (i.e. 62% of 3345 ≈ 2070 events), which occur in the period between November and February.
- The above number of air-mass thunderstorms is increased by an arbitrary 40% (i.e. 2070 x 1.4 ≈ 2900) to account for the entire summer season (i.e. from August to March).
- Assuming the area covered by the Bethlehem radar to be representative of Zone 1 (with $A_1$ of 875 000 km$^2$, see Table 9.3), this produces about 58 000 events (i.e. 2900 x 875 000 / 44 000), and 60 000 (=n$_1$) air-mass thunderstorm events per year, which is the number adopted for Zone 1.

Zone 2
For Zone 2, the life cycle of a typical strong thunderstorm is assumed to last between ½ and 1 hour. This corresponds to 18% of events (i.e. 18% of 3345 ≈ 600 events), which occur in the period between November and February and ±850 for the entire summer season. This translates to about:

$850 \times 390 000 / 44 000 \approx 7500 (=n_2)$

events for the entire Zone 2.
Zone 3  Only about 10 intense / severe thunderstorms per year occur in the radar area of Bethlehem. This translates to about 50 (=n_3) events for the entire Zone 3.

Zone 3 also experiences the occurrence of downbursts and tornadoes. The information on the occurrence of tornadoes in South Africa can be based on Goliger et al (1997). There are no statistics on the occurrence of downbursts in South Africa.

**Evaluation**

Consider a point in Gauteng region, which is overlapped by Zones 1, 2 and 3, and will therefore experience all types of thunderstorm events. The number of times per year that this point will be subject to thunderstorm events generating wind speeds greater than 15 m/s can be expressed as:

\[
N = \sum n_k \cdot a_{ki} / A_k = n_1 \cdot a_{1i} / A_1 + n_2 \cdot a_{2i} / A_2 + n_3 \cdot a_{3i} / A_3
\]

Where the \(A_k, n_k\) and \(a_{ki}\) are given in Table 9.3.

The resulting average number of times per year that the point will be exposed to thunderstorm activity with wind speeds larger than 15 m/s is then obtained as:

\[
N \approx 15 + 10 + 0.5 \approx 25 \text{ occurrences/year}
\]

**Table 9.3: Generic areas and rates of occurrence**

<table>
<thead>
<tr>
<th>zone k</th>
<th>area of the zone; (A_k (\text{km}^2))</th>
<th>number of thunderstorms; (n_k)</th>
<th>area with wind speeds &gt;15m/s; (a_{ki} (\text{km}^2)^*)</th>
<th>number of times per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>875 000</td>
<td>60 000</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>390 000</td>
<td>7 500</td>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>225 000</td>
<td>50</td>
<td>2 000</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\(^*\) from Table 9.2

This compares reasonably with Gauteng statistics on:

- the number of days (more than twenty) with rainfall greater than 10 mm (WB40, 1984) - which is typically due to thunderstorm events, and
- the average of 50 days with thunder (note that not all thunderstorms affect a specific area, in other words the thunder can be heard but the storm does not always pass over a particular locality).
Furthermore, the rate of occurrence of intense thunderstorms which was obtained, namely 0.5 per year per km$^2$, appears to be a reasonable figure. For example in the last 4-5 year period only three intense thunderstorms crossed the greater metropolitan area of Pretoria.

9.5.2 Frontal / coastal winds (Zones 4-7)

The average number of occurrences for Zones 4-7 has been adopted on the basis of the expertise of the Weather Bureau personnel listed in Section 8.1.

The following rates have been adopted:

Zone 4:
- 20 less severe events per year (with the peak wind speeds of 20 m/s), and
- 10 more severe events, with wind speeds of 30 m/s.

Zone 5:
- 10 events per year.

This translates to:
\[ \frac{10 \times 35,000}{120,000} = \text{ca. 3 occurrences per kilometre square per year}. \]

Zone 6:
The average duration of shallow south-easterly winds is between one and two days, although several such events often develop consecutively, and the total duration (including periods of calm) appears to be 3-5 days. A typical example of such winds is the famous 'Cape Doctor'. For the purpose of the current study, ten spells of three independent events (i.e. 10 x 3) are assumed, resulting in 30 events per year. This translates to:
\[ \frac{30 \times 25,000}{60,000} = \text{ca. 13 occurrences per kilometre square per year}. \]

Zone 7:
Between five and ten events occur per year and a total of 8 events has been assumed for the current project.
9.6 Summary

The information presented in Chapter 9 is summarised in Table 9.4. It has to be stressed that due to the way in which this data was obtained, it has to be treated as a 'first-approximation' only. However, in the absence of other relevant information, this data forms a starting point for further study and refinement.

Any additional research in this respect should be primarily oriented at a more accurate description of the extent of the zones and the yearly occurrence of frontal / coastal events.

### Table 9.4: Summary of information on strong wind events

<table>
<thead>
<tr>
<th>no</th>
<th>type of event</th>
<th>occurs in zones</th>
<th>generic footprint (km$^2$)</th>
<th>extreme wind speeds m/s</th>
<th>occurrence per year per km$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>width</td>
<td>length</td>
<td>area</td>
</tr>
<tr>
<td>1</td>
<td>weak/moderate thunderstorm</td>
<td>1, 2, 3</td>
<td>10</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>strong thunderstorm</td>
<td>2, 3</td>
<td>12.5</td>
<td>35</td>
<td>500</td>
</tr>
<tr>
<td>3.1</td>
<td>intense thunderstorm</td>
<td>3</td>
<td>17.5</td>
<td>100</td>
<td>2000</td>
</tr>
<tr>
<td>3.2</td>
<td>downburst</td>
<td>3</td>
<td>3</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>3.3</td>
<td>tornado</td>
<td>3</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>4</td>
<td>coastal-low buster</td>
<td>4</td>
<td>850</td>
<td>55</td>
<td>(50 000)</td>
</tr>
<tr>
<td>5</td>
<td>cut-off low east and west</td>
<td>5</td>
<td>350</td>
<td>100</td>
<td>(35 000)</td>
</tr>
<tr>
<td>6</td>
<td>coastal-low shallow SE</td>
<td>6</td>
<td>500</td>
<td>50</td>
<td>(25 000)</td>
</tr>
<tr>
<td>7</td>
<td>mid-latitude low</td>
<td>7</td>
<td>700</td>
<td>700</td>
<td>(480 000)</td>
</tr>
</tbody>
</table>

* depends on size, according to Fujita classification

** based on Goliger et al 1997 (irrespective of wind speeds)

( ) refers to total area of exposure

The last column of Table 9.4 gives the approximate values of the number of occurrences of various types of events per year per kilometre square within the respective zones of occurrence. This information can be readily used for disaster management purposes in order to determine the total area at risk for various types of wind events and for a specific area / district of concern.
Chapter 10
10 HUMAN BUILT DEVELOPMENT

Apart from wind climatic factors, the risk of damage depends on the spatial extent of human built development, the density of development and distribution of wealth and finally the structural strength of the various amenities which form the built environment.

10.1 The relevance of spatial distribution / extent

Of critical importance from a disaster management point of view is the geographical distribution and spatial extent of human built development in relation to the extent of the prevailing zones of occurrence of strong winds and the spatial extent of the potentially devastating wind events i.e. their footprints.

For example, for historical and economic reasons, several major cities in South Africa developed in the coastal areas which are subject to frontal depression winds. From the spatial occurrence point of view, however, their actual geographical positioning is of little relevance in relation to the vast geographical extent of the zones subject to frontal winds. For these cities the local characteristics of the coastline and topographical features in relation to the directions of the prevailing frontal winds (e.g. presence of the dominant topography over the Cape Peninsula) are much more important.

By contrast, it might be relevant for an inland development whether it is positioned in a region where intense thunderstorms occur (which could generate extreme wind events) or not. (For instance this issue recently became a major concern of the owners of a large commercial complex in South Africa, which among other things, includes the national storage facilities for high-value electronic goods.)

For elongated (line-like) structures like power lines, which extend for long distances, the probability of wind damage somewhere along the line becomes greater (almost inevitable if one considers a longer time period e.g. a season or a year). For disaster management of such structures, the issue of the extent (i.e. total length) over various wind zones becomes important, and power supply organisations across the world (including South Africa) take this into account in their disaster contingency and recovery plans.
10.2 Distribution of development and assets

The potential human loss as well as the risk of damage within an area or district of concern depends on the spatial extent of the built environment and this is the most relevant aspect for disaster management. For example, severe wind events which cross sparsely populated or underdeveloped areas often go unnoticed due to the lack of damage. The opposite can also be observed where relatively insignificant wind events tend to be exaggerated as soon as they impact negatively on human habitat.

10.2.1 Population distribution

Intuitively, a good indicator and starting point for establishing the extent and distribution of the built environment could be a map of population distribution. (This follows the argument that the presence of a built environment will correlate with the availability of work and habitat facilities.)

In Figure 10.1 a population density map for South Africa is presented (RDP, 1995). This map gives the average number of people per kilometre square per magisterial district. It can clearly be seen that the biggest population centres in South Africa are Gauteng and KwaZulu-Natal, followed by the Northern Province, and the greater metropolitan centres of Cape Town and Port Elizabeth. These population centres coincide with Zones 2 and 3 of inland winds and 4 and 5 of coastal winds (Figure 8.1).

10.2.2 Distribution of assets

It could be argued that population distribution maps would only be representative (in respect of the distribution of development and wealth) to the developed countries of the world, where wealth and development would correlate with the distribution of the economically active population. In developing countries (including South Africa) with large economic disparities, this is less applicable. One way of correcting for this would be to use a correction factor related to geographical distribution of income per capita, or disposable income.

Figure 10.2 is a map of the average income per capita, derived from the income per magisterial district divided by the total population of the district, (RDP, 1995). Clear differences between Figures 10.1 and 10.2 can be noted, particularly with reference to the Northern and Western Cape and other northern provinces of South Africa. (For the example sparsely populated Northern Cape has relatively high income per capita.) Figure 8.1 shows
Figure 10.1: Map of population density

Figure 10.2: Distribution of income per capita
that the north-central areas of the country (i.e. Gauteng) with relatively high income per capita are subject to the occurrence of strong and intense thunderstorms. By its nature the built environment is not uniform in either its density or replacement cost (or wealth) and this is important from a disaster management point of view. To illustrate this, consider two different scenarios of the distribution of assets within an area of concern, namely:

- an area with large uniformly distributed development wealth of relatively low replacement value, which implies a higher probability (i.e. the frequency) of damaging winds affecting the assets at stake, and
- an area of the same size, mostly undeveloped with a concentrated pocket of development with a high level of wealth, for which the average risk of damage is smaller but the consequence of a single event enveloping the asset concentration might be significant or even grave, and several such cases have been reported in South Africa (Welkom, Umtata or Cape Flats).

10.2.3 Informal development

Informal developments are an important component of the built environment in South Africa, and serve a large portion of society. In most cases these developments represent housing (or human shelter in the broadest sense) and Figure 10.3 presents the distribution of informal housing in the country (RDP, 1995). This distribution was derived from the percentage of housing which was considered to be informal (defined as built with unconventional building materials (RDP, 1995)) in both urban and rural areas. It can be seen that informal housing dominates (more than 75% of housing units) all densely populated parts of the country e.g. KwaZulu-Natal, parts of the Eastern Cape, as well as the northern provinces. In the Northern and Western Cape which have low population densities but which include the informal settlements of Khayelitsha and Cape Flats, less than 25% of houses are considered to be informal.

The amenities which make up informal developments receive no technical or engineering inputs and are not subject to any approval and inspection procedures. Furthermore, in most cases the cheapest possible (and / or substandard), often second hand, materials and assembly technologies are used. Such amenities are often the worst affected components and areas of devastation by strong wind events in South Africa. Although the financial consequences of the actual damage might be relatively low, the human effects can be devastating (i.e. death, injury or loss of entire households). Furthermore in view of the size of the affected communities, the overall cost of immediate disaster relief activities could be substantial.
10.2.4 Distribution of economic activities

Other relevant indicators of the spatial distribution of development and assets on both national and regional levels, are the geographical maps of various aspects of economic activity in the country. For example these could be indicators of the:

- level of urbanisation,
- manufacturing or agricultural product,
- electrical energy consumption and sales of liquid fuels,
- industrial product, or
- transportation and energy networks.

Figure 10.4 presents the major electrical grid of the South African electricity utility company (ESKOM). The spatial distribution of this network constitutes an excellent indicator of the demand and consumption of electric power and therefore the distribution of general economic activity within the country. Figure 10.5 depicts the distribution of major urban nodes and dense settlements in South Africa.
Figure 10.4: South African major electricity grid

Figure 10.5: Distribution of major urban nodes and dense settlements
10.3 Replacement costs per unit area

Apart from human loss and immediate relief activities, the most important aspect from the disaster management point of view is the prediction of the overall economic impact of wind (or other) disasters. The accumulated loss can be derived by integrating the predicted losses per unit area of the affected human built development.

To obtain such data, one would need statistical information on the initial replacement costs of the human amenities per unit area, and for various levels of development density and wealth. No such information is available for South Africa, especially not one that would take into account all types of amenities i.e. also informal human built developments.

Due to the nature of its business, the insurance sector operates within the formal sector of the built environment only. For re-insurance purposes, which are more relevant from a disaster management perspective, the distribution of wealth within a country or a geographical region is described in terms of the so-called Accumulation Assessment Zones, which take into account the total insured values per region. For South Africa 16 accumulation zones are identified as presented in Figure 10.6 (Munich Re, 1999). It can be seen that in some cases these zones correspond to the geographical extent of provinces (e.g. Zone 3 represents KwaZulu-Natal), while others combine provinces with similar levels of economic activity (Zone 1 includes Mpumalanga, the Northern Province and North-West Province). Individual zones are allocated to economic hubs like Cape Town (Zone 8) or Port Elizabeth (Zone 13).

10.4 Vulnerability curves

The vulnerability curves represent the relationship between the magnitude of wind speeds and the extent (i.e. percentage) of damage to built environment (i.e. the assets). This has been discussed in Section 3.4.2.2.

No vulnerability curves for South Africa are available and the information which appears in the international literature is incomplete due to its confidential nature.

In South Africa, as in other developing countries, a large proportion of structures (and therefore assets) receives little or no engineering input during the planning and construction phases. These structures will also have to be included in any risk assessment model.
A set of realistic assumptions can be made in respect of possible South African vulnerability curves, in which the:

- informal structures would fail at lower wind speeds than formal structures;
- progressive monetary value of damage is typically small at low wind speeds, and
- at high magnitudes of wind speed and once the integrity of a structure has been affected, a small increase in wind speed produces a greater increase in damage.

Accumulation Assessment Zones

![Accumulation Assessment Zones](image_url)

Figure 10.6: Accumulation Assessment Zones
Chapter 11
11 APPLICATION EXAMPLE OF THE MODEL

Apart from the human loss, the most important aspect from a disaster management point of view is the prediction of the average financial loss, per unit time, for the area of concern. In the current section an application of the model and mathematical procedure, with respect to financial implications, is demonstrated on the basis of a worked example. The densely populated and industrialised Magisterial District of Vanderbijlpark (in Gauteng) has been selected. The total area $A$ of the district is about 1 125 km$^2$.

Initially the input data on the distribution of the built environment in the Vanderbijlpark district is developed (Sections 11.1 and 11.2). This is based on a GIS database system and assumptions related to the distribution of asset values. Subsequently the occurrence of relevant strong wind events is defined (Section 11.3) on the basis of the information presented in Chapters 8 and 9.

The principles of the model and algorithm are then applied in order to determine:

- the extent of areas subject to the threshold wind speeds (Section 11.3),
- the probabilities of wind speed occurrence over these areas; initially irrespective of the extent of development and subsequently over the developed areas (Section 11.5), and
- the total developed area subject to ranges of wind speeds (Section 11.6).

Generic vulnerability curves are arbitrarily adopted on the basis of several assumptions, as presented in Section 11.7. This is followed by the determination of the average accumulated loss per kilometre square (Section 11.8) and the estimation of total loss (Section 11.9).

Where possible the information is presented in a tabular / matrix form, supported by graphs to enhance the ease of presentation of various steps and to accommodate the volume of data.

11.1 Distribution of human built development and wealth

Initially the feasibility of using a GIS-based map of land usage and cover in South Africa was investigated (CSIR SAC, 1996). This map is presented in Figure 11.1. Unfortunately due to the format of the data, in which the individual polygons also extend over neighbouring
magisterial districts, it was not possible to adopt this information for the purpose of the current study.

In view of the absence of any other relevant data in a suitable format, a map of the total population distribution (StatsSA, 1996) has been selected for the current application. Following discussions with the CSIR’s GIS modellers and initial trials, four generic population densities were selected for the GIS modelling of Vanderbijlpark as follows:

- $d_1$ - between 0 and 200 people per km$^2$,
- $d_2$ - between 201 and 500 people per km$^2$,
- $d_3$ - between 501 and 2000 people per km$^2$, and
- $d_4$ - between 2001 and 6000 people per km$^2$.

The resulting map of population densities, which was derived from the GIS modelling process is presented in Figure 11.2.

The built environment within the area of interest is variable with a fair mix of formal and informal structures. It is therefore difficult determine representative figures of average asset values (per kilometre square of development) for each of the population densities stipulated above. Four generic levels of asset values were, therefore, adapted to be:

- $m_1$ – R3m per km$^2$,
- $m_2$ – R5m per km$^2$,
- $m_3$ - R20m per km$^2$, and
- $m_4$ – R500m per km$^2$. 
Figure 11.1: Vanderbijlpark Magisterial District: land use cover
Figure 11.2: Vanderbijlpark Magisterial District: population distribution
11.2 Areas of development densities

The GIS map presented in Figure 11.2 was converted to a CAD system in order to measure the total area of the four asset densities. (Because of the definition (resolution) of the GIS polygons, direct use of the GIS system proved to be less advantageous.) The CAD Area Polygon Function was used to determine the areas as below:

- \( \sum s_n (d_1) = \sum m_1 (s_n) = 202 \text{ km}^2 \),
- \( \sum s_n (d_2) = \sum m_2 (s_n) = 702 \text{ km}^2 \),
- \( \sum s_n (d_3) = \sum m_3 (s_n) = 220 \text{ km}^2 \), and
- \( \sum s_n (d_4) = \sum m_4 (s_n) = 1 \text{ km}^2 \).

It can be seen that the above distribution of the number of kilometres square with various development densities is not typical. This refers to the asset values \( m_1 \) and \( m_2 \), in which a larger area (702 km\(^2\)) corresponds to a larger average asset values of the development. This is a reflection of the character (level of urbanisation) of the Vanderbijlpark district and, apart from the large cities, will not be representative of most areas of South Africa.

Furthermore, this situation demonstrates the unique influence of the spatial distribution of asset value on the exposure to wind damage and the ability of the model to address such influences. Future studies (using GIS technology) could be directed at identifying various spatial characteristics of representative cases of development. Such information could form the basis of future assessments of the proposed model.

11.3 Occurrence of strong wind events

The Vanderbijlpark Magisterial District lies within Zone 3 and can, therefore, be subject to the following types of strong wind events:

- weak to moderate thunderstorms,
- strong thunderstorms,
- severe thunderstorms,
- tornadoes, and
- downbursts and microbursts.
From Table 9.3 it can be determined that on average, the entire area will be subject to:

- 60 000 • 1 125 / 875 000 = ca. 75 weak / moderate thunderstorms,
- 7 500 • 1 125 / 390 000 = ca. 20 strong thunderstorms, and
- 50 • 1 125 / 225 000 = 0.25 say 1 severe thunderstorm, per year.

No statistics on the occurrence of downbursts is available (see Table 9.4), and the average number of three events for the entire area A per year has been adopted. In addition, for purposes of clarity and consistency of the example, an average occurrence of one tornado event per year (F2 on the Fujita scale) has been adopted for the Vanderbijlpark district. (This assumption is conservative.)

11.4 Areas subject to threshold wind speeds

The total number of kilometres square (∑a_i (V>/Vi)) exposed to the specific ranges of wind speeds due to the three types of thunderstorm events can be obtained by factorising the average number of strong wind events derived for area A (Section 11.3) from the matrix of generic footprints (Table 9.2) as presented in Table 11.1.

Table 11.1: Total number of km² exposed to ranges of wind speeds

<table>
<thead>
<tr>
<th>m/s</th>
<th>&gt;15</th>
<th>&gt;20</th>
<th>&gt;25</th>
<th>&gt;15</th>
<th>&gt;20</th>
<th>&gt;25</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>200</td>
<td>50</td>
<td>-</td>
<td>15 000</td>
<td>3 750</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>500</td>
<td>200</td>
<td>50</td>
<td>10 000</td>
<td>4 000</td>
<td>1 000</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
<td>500</td>
<td>200</td>
<td>2 000</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27 000</td>
<td>8 250</td>
<td>1 200</td>
</tr>
</tbody>
</table>

Note that in Table 11.1 the sign (i.e. notation) ≥ has been replaced with >. This simplification is justifiable in view of the approximate nature of the current example and will be used throughout this chapter.

For downburst events, three generic areas subject to the respective levels of wind speed have been selected (based on Figure 9.7) namely:

- wind speeds > 30 m/s - 15 km²,
- wind speeds > 40 m/s - 7.5 km², and
- wind speeds > 50 m/s - 1.5 km².
The area exposed to a tornado has been taken as 5 km$^2$ with wind speeds >50 m/s. Assuming three downbursts and one tornado event per year, the resulting areas subject to wind speeds will be obtained (approximated) as:
- with wind speeds > 30 m/s - 50 km$^2$,
- wind speeds > 40 m/s - 20 km$^2$, and
- wind speeds > 50 m/s - 10 km$^2$.

Finally, the total number of kilometres square which will, on average, be exposed to each threshold level of wind speed in one year can be summarised as:
- $\Sigma a (v>15 \text{ m/s}) = 27 000 \text{ km}^2$,
- $\Sigma a (v>20 \text{ m/s}) = 8 250 \text{ km}^2$,
- $\Sigma a (v>25 \text{ m/s}) = 1 200 \text{ km}^2$,
- $\Sigma a (v>30 \text{ m/s}) = 50 \text{ km}^2$,
- $\Sigma a (v>40 \text{ m/s}) = 20 \text{ km}^2$, and
- $\Sigma a (v>50 \text{ m/s}) = 10 \text{ km}^2$.

The relationship between the total number of kilometres square per year subject to the threshold levels of wind speed can then be plotted as in Figure 11.3. Two marked characteristics of the resultant curve have to be raised.

Figure 11.3: Total number of km$^2$ subject to threshold wind speeds

A rapid increase in wind speeds corresponding to areas smaller than $10^2$ km$^2$ can be noted. This is because the rate of occurrence and footprints of thunderstorms are significantly larger than those due to high intensity winds (i.e. downbursts and tornadoes). In fact the
curve presented in Figure 11.3 is a combination of two contributions: one due to thunderstorms and the other due to high intensity winds. This is also a fair reflection of a typical full-scale situation where, within the broad damage over a large area, localised pockets of intense damage are often evident.

In addition, the apparent hump in distribution, corresponding to an area greater than 1 000 km$^2$, is to be expected. This is due to the size of the area density $d_2$ in relation to $d_1$, which could be typical for densely populated administrative regions and cities. This was discussed in Section 11.2.

11.5 Wind speed rate of occurrence

The rate of occurrence (or number of times per annum) that, on average, one kilometre square within the area $A$ will be subject to different ranges of wind speeds can then be obtained by normalising the areas presented in Figure 11.3 by the total area of region $A$:

- $R(v>15) = \frac{27 000 \text{ km}^2}{1 125 \text{ km}^2} = \text{ca. 25}$
- $R(v>20) = \frac{8 250 \text{ km}^2}{1 125 \text{ km}^2} = \text{ca. 7}$
- $R(v>25) = \frac{1 200 \text{ km}^2}{1 125 \text{ km}^2} = \text{ca. 1}$
- $R(v>30) = \frac{50 \text{ km}^2}{1 125 \text{ km}^2} = \text{ca. 0,05}$
- $R(v>40) = \frac{20 \text{ km}^2}{1 125 \text{ km}^2} = \text{ca. 0,02}$
- $R(v>50) = \frac{10 \text{ km}^2}{1 125 \text{ km}^2} = \text{ca. 0,01}$

per year per kilometre square as plotted as in Figure 11.4.

![Figure 11.4: Rate of occurrence of wind speeds larger than the threshold levels](image-url)
The spatial contribution of each density of assets (i.e. the ratios of areas of various densities of assets towards the total area $A$) can be expressed as:

- $\sum m_1 (s_n) / A = 202 \text{ km}^2 / 1125 \text{ km}^2 = \text{ca. 0.18}$
- $\sum m_2 (s_n) / A = 702 \text{ km}^2 / 1125 \text{ km}^2 = \text{ca. 0.62}$
- $\sum m_3 (s_n) / A = 220 \text{ km}^2 / 1125 \text{ km}^2 = \text{ca. 0.20}$
- $\sum m_4 (s_n) / A = 1 \text{ km}^2 / 1125 \text{ km}^2 = \text{ca. 0.001}$

The rate of occurrence (number of times) of various threshold wind speeds striking a one km$^2$ with an asset density $m_1$ can then be determined as:

- $R_{m_1}(v>15) = 25 \times 0.18 = \text{ca. 4.5}$
- $R_{m_1}(v>20) = 7 \times 0.18 = \text{ca. 1.25}$
- $R_{m_1}(v>25) = 1 \times 0.18 = \text{ca. 0.2}$
- $R_{m_1}(v>30) = 0.05 \times 0.18 = \text{ca. 0.01}$
- $R_{m_1}(v>40) = 0.02 \times 0.18 = \text{ca. 0.004}$
- $R_{m_1}(v>50) = 0.01 \times 0.18 = \text{ca. 0.002}$

Similar calculations can be made for densities $m_2$, $m_3$ and $m_4$ and the resultant values form the information included in Table 11.2.

### Table 11.2: Occurrence of threshold wind speeds striking a km$^2$ of an asset density

<table>
<thead>
<tr>
<th>$v_i$</th>
<th>$&gt;15 \text{ m/s}$</th>
<th>$&gt;20 \text{ m/s}$</th>
<th>$&gt;25 \text{ m/s}$</th>
<th>$&gt;30 \text{ m/s}$</th>
<th>$&gt;40 \text{ m/s}$</th>
<th>$&gt;50 \text{ m/s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{m_1}(v&gt;v_i)$</td>
<td>4.5</td>
<td>1.25</td>
<td>0.2</td>
<td>0.01</td>
<td>4 $\times 10^{-3}$</td>
<td>2 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$R_{m_2}(v&gt;v_i)$</td>
<td>15.5</td>
<td>4.3</td>
<td>0.6</td>
<td>0.03</td>
<td>1.2 $\times 10^{-2}$</td>
<td>6 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$R_{m_3}(v&gt;v_i)$</td>
<td>5</td>
<td>1.4</td>
<td>0.2</td>
<td>0.01</td>
<td>4 $\times 10^{-3}$</td>
<td>2 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$R_{m_4}(v&gt;v_i)$</td>
<td>2.5 $\times 10^{-2}$</td>
<td>7 $\times 10^{-3}$</td>
<td>1 $\times 10^{-3}$</td>
<td>5 $\times 10^{-5}$</td>
<td>2 $\times 10^{-5}$</td>
<td>1 $\times 10^{-5}$</td>
</tr>
</tbody>
</table>

### 11.6 Total areas subject to wind speed ranges

The total exposure area (number of kilometres square) within each asset density that will, on average, be subject to various threshold wind speeds per year can be determined by multiplying the above probabilities by the total areas corresponding to each density of development (i.e. for density $d_1(m_1)$ the number of kilometres square subject to wind speeds greater than 15 m/s will be 202 km$^2 \times 4.5 = 909$ km$^2$). The results are tabulated in Table 11.3 and presented graphically in Figure 11.5.
Table 11.3: Total exposure area in km$^2$ subject to various threshold wind speeds

<table>
<thead>
<tr>
<th>$v_i$</th>
<th>&gt;15 m/s</th>
<th>&gt;20 m/s</th>
<th>&gt;25 m/s</th>
<th>&gt;30 m/s</th>
<th>&gt;40 m/s</th>
<th>&gt;50 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sum s_{m1}(v&gt;v_i)$</td>
<td>909</td>
<td>253</td>
<td>40</td>
<td>2</td>
<td>1</td>
<td>0,5</td>
</tr>
<tr>
<td>$\sum s_{m2}(v&gt;v_i)$</td>
<td>10 880</td>
<td>3020</td>
<td>420</td>
<td>21</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>$\sum s_{m3}(v&gt;v_i)$</td>
<td>1 100</td>
<td>308</td>
<td>44</td>
<td>2</td>
<td>1</td>
<td>0,5</td>
</tr>
<tr>
<td>$\sum s_{m4}(v&gt;v_i)$</td>
<td>2.5\times10^{-2}</td>
<td>7 \times 10^{-3}</td>
<td>1 \times 10^{-3}</td>
<td>5 \times 10^{-5}</td>
<td>2 \times 10^{-5}</td>
<td>1 \times 10^{-5}</td>
</tr>
</tbody>
</table>

Figure 11.5: Total exposure area in km$^2$ for each development asset value exposed to threshold levels of wind speeds

In order to avoid the duplication of loss, the total area(s) subject to the ranges of wind speeds has to be derived by deducting from each of the above values the value corresponding to the higher threshold wind speed. For example, in the first row and column the actual area subject to wind speeds between 15 and 20 m/s will be 909 - 253 = 656 km$^2$, etc. Table 11.3 will then convert to Table 11.4 as below:

Table 11.4: Total exposure area in km$^2$ subject to ranges of wind speeds

<table>
<thead>
<tr>
<th>$v_i$</th>
<th>15&lt;v&lt;20</th>
<th>20&lt;v&lt;25</th>
<th>25&lt;v&lt;30</th>
<th>30&lt;v&lt;40</th>
<th>40&lt;v&lt;50</th>
<th>&gt;50 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta s_{m1}(v&gt;v_i)$</td>
<td>656</td>
<td>213</td>
<td>38</td>
<td>1</td>
<td>0,5</td>
<td>0,5</td>
</tr>
<tr>
<td>$\Delta s_{m2}(v&gt;v_i)$</td>
<td>7 780</td>
<td>2600</td>
<td>399</td>
<td>13</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\Delta s_{m3}(v&gt;v_i)$</td>
<td>792</td>
<td>284</td>
<td>42</td>
<td>1</td>
<td>0,5</td>
<td>0,5</td>
</tr>
<tr>
<td>$\Delta s_{m4}(v&gt;v_i)$</td>
<td>1.8\times10^{-2}</td>
<td>6 \times 10^{-3}</td>
<td>1 \times 10^{-3}</td>
<td>3 \times 10^{-5}</td>
<td>1 \times 10^{-5}</td>
<td>1 \times 10^{-5}</td>
</tr>
</tbody>
</table>
It has to be stressed that the above exposure areas do not relate in any way the size of the Vanderbijlpark Magisterial District but represent the total number of square kilometres at risk due to strong wind events, which occur in one year. In other words if on average a strong wind event with a specific threshold of wind speed will occur 10 times per year per kilometre square, in statistical terms this implies that in effect 10 times more square kilometres will be exposed to that wind speed. This assumes the homogenous distribution of events and assets and furthermore that the damage due to a strong wind event will be repaired before the same area is exposed to another damaging event.

The information included in Table 11.4 regarding the number of kilometres square of developed areas subject to various ranges of strong winds can also serve as an indicator of the affected population or number of households in the areas subject to strong wind events per year.

The potential areas subject to wind speeds greater than 30 m/s, which is the threshold speed of danger to the human body (Chapter 5.7), can be extracted from Table 11.4 and summarised as in Table 11.5. (Note that in this table the areas with development density \( m_4 \) have been ignored, and furthermore the average population densities were adopted as median values of the densities identified in Section 11.1) These areas can be factorised by the respective population densities to determine the overall number of people that could be affected by the event.

<table>
<thead>
<tr>
<th>( v_i \rightarrow )</th>
<th>( 30&lt;v&lt;40 )</th>
<th>( 40&lt;v&lt;50 )</th>
<th>&gt;50 m/s</th>
<th>total areas</th>
<th>population density</th>
<th>population per area density</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta s_{m1}(v&gt;v_i) )</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>2</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>( \Delta s_{m2}(v&gt;v_i) )</td>
<td>13</td>
<td>4</td>
<td>4</td>
<td>21</td>
<td>350</td>
<td>7350</td>
</tr>
<tr>
<td>( \Delta s_{m3}(v&gt;v_i) )</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>2</td>
<td>1250</td>
<td>2500</td>
</tr>
</tbody>
</table>

predicted total population affected by strong wind events per year ca.10 000

As discussed the actual number of people at risk (i.e. exposed to severe winds) will be significantly lower. A similar calculation can be performed in respect of the number housing units at risk. For this, the data on the average number of households per unit area would be necessary.
11.7 Vulnerability curves

In view of the lack of any data on the vulnerability of the built environment in South Africa, three generic curves have been stipulated arbitrarily as presented in Figure 11.6. The corresponding percentage of damage, %Dm, for each asset density, in terms of the threshold levels of wind speed, are presented in Table 11.6.

![Figure 11.6: Proposed vulnerability curves for asset values m₁ – m₄]

<table>
<thead>
<tr>
<th>v₁ →</th>
<th>&gt;15 m/s</th>
<th>&gt;20 m/s</th>
<th>&gt;25 m/s</th>
<th>&gt;30 m/s</th>
<th>&gt;40 m/s</th>
<th>&gt;50 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>%Dm₁(v&gt;v₁)</td>
<td>0</td>
<td>0,5</td>
<td>0,5</td>
<td>15</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>%Dm₂(v&gt;v₁)</td>
<td>0</td>
<td>0</td>
<td>0,25</td>
<td>0,25</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>%Dm₃(v&gt;v₁)</td>
<td>0</td>
<td>0</td>
<td>0,25</td>
<td>0,25</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>%Dm₄(v&gt;v₁)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0,5</td>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

The vulnerability curves were developed on the basis of the following assumptions:

- Greater density of development corresponds to 'more engineered' and therefore more wind resistant structures. (It was assumed that in denser areas 'the industrial component' will form a larger proportion of structures.)
A single vulnerability curve has been adopted for development and asset values $m_2$ and $m_3$, by assuming that within those densities the average level of engineering input (i.e. wind resistance), would be similar.

The initial failure of the most vulnerable components of buildings and their surroundings (e.g. roof tiles, windows, fences etc.) will start at wind speeds of 20-30 m/s. However, these components constitute a fraction of the total value of built environment, and therefore it was assumed that:
- for the areas with asset value $m_1$, damage corresponding to 0.5% of the asset value will develop at wind speeds between 20 and 25 m/s,
- for asset values $m_2$ and $m_3$, damage corresponding to 0.25% of the asset value will develop at wind speeds between 25 and 30 m/s, and
- for asset value $m_4$, damage corresponding to 0.5% of the asset value will develop at wind speeds between 30 and 35 m/s.

All structures in areas with an asset value of $m_1$, will be totally destroyed at wind speeds that reach the threshold of 40 m/s.

An upper limit wind speed of 50 m/s was considered. It was assumed that at this level of wind speed, the average damage to all structures in areas with asset values $m_2$, $m_3$ and $m_4$ would be less than 50%. This follows from the assumption that a fair proportion of the asset values would relate to infrastructure, concrete and heavy steel substructures, which would not be damaged.

11.8 Accumulated loss per km$^2$

The percentages of damage per kilometre square presented in Section 11.7 can be converted to monetary terms by factorising them by the average asset values (i.e. 3, 5, 20 and R500m). The corresponding matrix of the average accumulated loss $L_{mi}$ per kilometre square, per year is presented in Table 11.7 and Figure 11.7.
Table 11.7: Accumulated loss per km² (in Rm)

<table>
<thead>
<tr>
<th>(v_i \rightarrow)</th>
<th>(&gt;15,\text{m/s})</th>
<th>(&gt;20,\text{m/s})</th>
<th>(&gt;25,\text{m/s})</th>
<th>(&gt;30,\text{m/s})</th>
<th>(&gt;40,\text{m/s})</th>
<th>(&gt;50,\text{m/s})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{m1}(v&gt;v_i))</td>
<td>0</td>
<td>0,015</td>
<td>0,015</td>
<td>0,45</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>(L_{m2}(v&gt;v_i))</td>
<td>0</td>
<td>0</td>
<td>0,0125</td>
<td>0,0125</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>(L_{m3}(v&gt;v_i))</td>
<td>0</td>
<td>0</td>
<td>0,05</td>
<td>0,05</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>(L_{m4}(v&gt;v_i))</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2,5</td>
<td>50</td>
<td>150</td>
</tr>
</tbody>
</table>

Figure 11.7: Average accumulated loss per km² per year for each asset value

11.9 Estimation of total loss

The average loss per year for each of the asset values exposed to various ranges of wind speeds can be obtained by multiplying the corresponding values included in the matrices of:

- the total number of kilometres square within each asset value of development that will on average be exposed to various ranges of wind speeds per year (Table 11.4), and
- the average accumulated loss per kilometre square as a result of exposure to the threshold wind speeds (Table 11.7).

The resultant matrix is presented in Table 11.8.
Table 11.8: The average loss per year (in Rm)

<table>
<thead>
<tr>
<th>$v_i \rightarrow$</th>
<th>$&gt;15 \text{ m/s}$</th>
<th>$&gt;20 \text{ m/s}$</th>
<th>$&gt;25 \text{ m/s}$</th>
<th>$&gt;30 \text{ m/s}$</th>
<th>$&gt;40 \text{ m/s}$</th>
<th>$&gt;50 \text{ m/s}$</th>
<th>per dev. density</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma L_{m1}(v&gt;v_i)$</td>
<td>0</td>
<td>3.2</td>
<td>0.6</td>
<td>0.5</td>
<td>1.5</td>
<td>-</td>
<td>5.8</td>
</tr>
<tr>
<td>$\Sigma L_{m2}(v&gt;v_i)$</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0.2</td>
<td>4</td>
<td>8</td>
<td>17.2</td>
</tr>
<tr>
<td>$\Sigma L_{m3}(v&gt;v_i)$</td>
<td>0</td>
<td>0</td>
<td>2.1</td>
<td>~0</td>
<td>2</td>
<td>4</td>
<td>8.1</td>
</tr>
<tr>
<td>$\Sigma L_{m4}(v&gt;v_i)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>~0</td>
<td>~0</td>
<td>~0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>3.2</td>
<td>7.7</td>
<td>0.7</td>
<td>7.5</td>
<td>12</td>
<td>31.1</td>
</tr>
</tbody>
</table>

Grand total approximately 30 Rm

The accumulated average loss for the entire magisterial district can then be obtained as a summation of the above figures, which comes to about R30m per year. Few important issues have to be raised regarding Table 11.8, namely:

- About $\frac{1}{3}$ of the loss is due to wind speeds less than 30 m/s.

- A large portion of the above loss will be due to minor damage occurring over a large contributory area. Such damage typically corresponds to broken glass and lost or broken tiles and the cost per housing unit is in the order of R500 or less. Such loss has more of a social impact but repairs are carried out at the expense of the owners or residents of the properties and the damage therefore often goes unreported. Furthermore, this type of damage is not relevant to disaster management activities and is not covered by insurance agencies.

- The amount of R30m appears to be high. This is due to the contribution of wind speeds greater than 40 m/s, as a result of a conservative assumption regarding the number of downburst and tornado events (one and three, section 11.3).

The R30m given above reflects the total expected loss for the magisterial district which is likely to affect the built environment, on average per year. This does not imply, however, that a loss of such magnitude will occur each year. For disaster management purposes (i.e. contingency plans) such loss could rather be considered as cumulative over a longer period, say 3-5 years. In other words, for disaster management purposes, longer time periods should be considered in combination with more severe events as opposed to frequent events of lesser consequences.
Interesting trends can be observed in Table 11.8 in which relatively little total damage is due to wind speeds greater than 30 m/s. This is due to a very small contribution of the accumulated loss per km² (Table 11.7) and in turn to the character of the vulnerability curves which were adopted (Table 11.6), namely similar percentage of damage to that corresponding to wind speed of 25 m/s.

Another characteristic which is evident is that more than half the total loss is contributed by development density m², which represents 62% of the total area of the magisterial district.

Unfortunately as mentioned in Chapter 1 no statistics on losses attributable to windstorms in South Africa are kept and it is therefore not possible to evaluate this figure against damage and insurance claims history. However only recently (in December 2001) extensive wind damage which resulted in losses totalling several million rand, was reported over a larger region which includes the Vanderbijlpark Magisterial District.
Chapter 12
12 ASSESSMENT AND RELIABILITY CONSIDERATIONS

12.1 Assessment of principles

The dissertation consists of two basic components. The first presents background information on wind damage and disaster, and demonstrates its relevance to South Africa by analysing and processing the data of historical events. The factors which influence the magnitude of wind damage are identified and analysed in terms of the local content.

The second component presents the philosophy and development of a generic risk model of wind damage and disaster for application in disaster management activities. The basis of the proposed model is universal in the sense that it is founded on first principles of spatial statistics. In particular this refers to the probability of a unit area within a large uniform reference area, experiencing an event of relatively small reference area. This can be expressed in terms of the ratio of the event area over the reference area. This basic philosophy has been used elsewhere in the engineering sciences (e.g. geology and geotechnics) for the development of spatial relationships. In wind engineering it has been used to model the risk of tornadic events in the USA and South Africa as well as winter storms in Europe.

The spatial approach has been adopted for three reasons, namely:

- the poor coverage and representivity of recorded wind data in relation to the complexity and variety of climatic zones in South Africa,
- its suitability to disaster management applications, and
- the specific content of the built environment in South Africa, with a large component of informal development.

A generic algorithm is proposed. Due to the lack of relevant data for South Africa, the wind-related aspects of the model, which form the inputs to the algorithm, are investigated and developed. The development process of this data was based on the limited South African meteorological literature, relevant international information and the interpretation of the macro-climatic characteristics based on the expertise and experience of the South African Weather Service. In view of the manner in which the input information was developed, it should be treated as first-approximation data, open to future refinement and upgrade.

In the course of the project an innovative method of determining the generic wind extent (i.e. footprints) of South African thunderstorms was examined and adopted.
Finally an implementation of the proposed model and algorithm is demonstrated in terms of an example for a selected magisterial district in the interior of South Africa which is subject to all types of convective winds. The necessary input data related to the distribution of human development and the strength of structures has been assumed for the sake of demonstrating the model.

### 12.2 Reliability considerations

The reliability analysis of the current model would require an estimation of the levels of uncertainties in respect to the:

- land-cover factors, and
- wind / climatic factors.

The land-cover factors (highlighted in Chapter 10) refer in principle to the information on the distribution of human development and assets, as well as the resistance of various types of structures forming the built environment, which is represented by vulnerability curves. Most of these factors have strong spatial and time dependencies. Due to the nature of the current study these aspects of the risk model were not investigated and they will therefore not be considered in the current reliability analysis.

A discussion of the levels of uncertainty of the wind climatic factors described in Chapters 8 and 9 is presented in the following sections.

### 12.3 Confidence levels of wind input data

To start with, it is important to note that due to the stochastic (often considered as partially chaotic) nature of all types of climatic events, confidence levels relevant to the meteorological sciences are substantially lower than those in other engineering sciences. That is why the synoptic predictions of the weather services in various countries are still made on the basis of the general macro-climatic situation (obtained from computer modelling) combined with intuitive interpretation of various factors by the respective teams of forecasters. Such predictions are commonly referred to as the subjective probabilities of the arrival of certain types of weather.

The proposed risk model is based on a formulation and definition of three sets of stochastic quantities / components, namely the:
Superficially and in terms of the process, the results of the model are the weighted products of the above parameters in the sense that an increase in the extent of a specific type of a footprint by 10% will increase the total area subject to strong wind and thus amount of loss, by 10%. In combination, the dependencies are much more complex (and not linear) but the levels of confidence of the input quantities and components determine the overall confidence level of the occurrence of strong winds (i.e. wind loads).

Due to the nature of the current study on topics on which no research has ever been conducted in South Africa, no relevant statistics regarding the levels of confidence in the above quantities are available. Therefore the discussion in the following subsections can only be treated as an expert assessment of the likely levels of uncertainties within the generic components of the proposed model.

12.3.1 Zones of occurrence

Considering a specific geographic locality or district, the problem of uncertainty relates to the level of confidence in the extent of the zone in which this locality / district is assumed to reside. This in turn determines if the locality / district will be subject to the occurrence of the specific types of wind events which define the zone. This principle is presented schematically in Figure 12.1 for Zone 2.

![Figure 12.1: Uncertainties in the extent of a zone](image-url)
As was stressed in Section 8.1, in the current project the process of identifying the various zones was based on identifying the dominant types of strong wind events within each zone. This does not exclude the occurrence of specific types of events outside the specific zones as well as the occurrence of different types of strong wind events, which characterise other zones. For example, as mentioned in Section 8.2, coastal low-pressure systems can occasionally produce convective activity which was ignored while defining coastal Zone 6. Ironically, one of the most devastating tornadoes in South Africa (Cape Flats, August 1999) occurred in this geographical region.

Furthermore the model assumes that the defined zones are homogenous and, therefore, the probability that a specific geographic locality can be subject to two strikes of an extreme wind event with a small footprint (like a tornado or downburst) in one year is practically non-existent. However, in 1987 two tornadoes struck Piet Retief within a week of each other.

In view of the above discussion and after evaluating the issue with the SA Weather Service, a coefficient of variation ($c_{0.2}$) of between 0.10 and 0.25 in defining the spatial extent zones of strong wind events is proposed arbitrarily.

### 12.3.2 Footprints of wind events

The identification of the footprints of various types of strong wind events was based on three basic assumptions namely:

- for thunderstorms, on a correlation between the radar reflectivity index and peak wind speeds,
- for frontal events, on an assumption that the individual events envelop the entire zones of occurrence, and
- for extreme wind events (i.e. downbursts and tornadoes), on the basis of international literature.

The first assumption was discussed in Section 9.2. At that stage a relationship between the magnitude of radar reflectivity and wind speed of two-to-one (i.e. 2.0) was assumed, based on comparative data from five correlated records of these quantities. This arbitrary assumption was made because there is a limited number of records and because of the pilot nature of the investigation. A best-fit linear regression line (based on the least-square method) suggests a ratio of 2.12, and this is re-plotted in Figure 12.2. This figure includes lines representing the ±20% offset from the best-fit line (i.e. ratios 2.54 and 1.7), which give a fair reflection of the level of scatter.
The second assumption, regarding frontal winds, is based on the typical macro-climatic extent of these events, which is adopted for weather forecasting in South Africa. No data on the distribution wind speeds is, however, available as discussed in Section 9.4.

The extent of the footprints of extreme wind events (third assumption) was adopted on the basis of the overseas data. The applicability of this information to South African conditions could be debatable.

In summary more research is required to increase the accuracy of the proposed quantities and a coefficient of variation ($c_0'$) of between 0.15 and 0.40 is proposed.

12.3.3 Rate of occurrence

The rate of occurrence of thunderstorms has been established on the basis of a statistical analysis of a well-represented sample of data (i.e. more than three thousand events). However, extrapolation was used in the current project in order to account for the entire summer season and also other geographic regions not covered by the specific radar installation (Section 9.5.1).

The occurrence rate of frontal events was adopted on the basis of the general information used for coastal forecasting by the SA Weather Bureau Services (Hunter, 2000).
In view of the above, a coefficient of variation (\(c_{ov}\)) of between 0.15 and 0.25 is proposed.

### 12.4 Reliability

The probability distribution of wind speeds affecting a specific locality / region will be determined by a combination of probability distributions of the three factors, which can generally be expressed as:

\[
P_{w(s)} = P_z \cdot P_f \cdot P_r
\]

where the:
- \(P_{w(s)}\) refers to probability density of wind speed affecting locality / region \(s\),
- \(P_z\) is the probability distribution of the extent of the area defining the zones of strong wind events,
- \(P_f\) is the probability distribution of the extent of the generic foot-prints of strong wind events, and
- \(P_r\) is the probability distribution of the rate of occurrence of strong wind events.

This principle is presented schematically in Figure 12.3. Each of the distributions will be characterized by its own set of parameters, namely the mean values (\(z_{mean}\), \(f_{mean}\) and \(r_{mean}\)), coefficients of variation (\(c_{ov}z\), \(c_{ov}f\), and \(c_{ov}r\)) and respective standard deviations (\(\sigma_z\), \(\sigma_f\), and \(\sigma_r\)).

The overall level of uncertainty will be a combination of three of uncertainties. The proposed ranges of coefficients of variation discussed in Sections 12.3.1 to 12.3.3 are summarised in Table 12.1. Also included in Table 12.1 are the best estimate (i.e. the average values) as well as conservative point in time estimate values of the respective coefficients of variation. (By comparison a typical range of coefficients of variation used in wind loading statistics for buildings (e.g. regarding the magnitude of pressure coefficients or directional influence) varies between 0.1 and 0.2 (Ellingwood et al, 1980; Davenport, 1983)).
The Central Limit Theorem states that a probability distribution of a sum of independent random variables in which none dominates this sum, tends to be normal. In the case of a product of independent variables:

\[ Y = X_1 X_2 X_3 \]

a transformation can be used, which will allow one to apply the Central Limit Theorem, by taking a natural logarithm of both sides:

\[ \ln Y = \ln X_1 + \ln X_2 + \ln X_3 \]
This sum can be treated as the sum of a series of random variables and since $\ln Y$ is normal then $Y$ must be lognormal. With reference to the loadings of structures, this implies that in cases where the resultant loads and / or resistance is a product of independent statistical variables, the resulting distribution will be lognormal and will have a reasonable degree of stability.

Using the Central Limit Theorem, it can be shown that for statistically independent variables:

$$
\sigma^2_{\ln Y} = \ln \left( (c_{ov x1}^2 + 1) + \ln \left( (c_{ov x2}^2 + 1) + \ln \left( (c_{ov x3}^2 + 1) \right) \right) \right)
$$

and

$$
\left( (c_{ov x1}^2 + 1) \right) \left( (c_{ov x2}^2 + 1) \right) \left( (c_{ov x3}^2 + 1) \right)
$$

where $c_{ov x}$ is the coefficient of variation of function $Y$, and $c_{ov x n}$ the coefficient of variation of variable $X_n$.

For the current argument this can be re-written as:

$$
\left( (c_{ov w})^2 + 1 \right) = \left( (c_{ov x1}^2 + 1) \right) \left( (c_{ov x2}^2 + 1) \right) \left( (c_{ov x3}^2 + 1) \right)
$$

where the $c_{ov w}$ is the coefficient of variation in the wind input data of the proposed model (i.e. the factors related to the occurrence of strong winds). If one substitutes the values tabulated in Table 12.1 into the above equation, coefficients of variation $c_{ov w}$ of between 0.21 and 0.56 are obtained with the best estimate value of 0.4 and conservative estimate of 0.5.

It can be seen that, based on the ranges of coefficients of variation assumed for the current consideration (Table 12.1), a combined coefficient of variation of between 0.4 and 0.5 gives a fair reflection of the overall levels of uncertainty of the wind related factors in the proposed risk model.

12.5 The Turkstra approach

Taking into account the full non-linearity of the proposed model, the Turkstra rule might be applied to derive a reasonable estimate of the overall level of uncertainty. This approach is used for defining the load combinations in structural design (Turkstra, 1980; Milford, 1988). Following this approach one would assume that when one of the wind related factors reaches an extreme value, other factors are acting / contributing at their average values (i.e. point-in-time values). In other words, the possibility of uncertainties due to two or three
In this flowchart the data from a comprehensive inspection programme forms the input to the database on wind damage and the development of relevant statistics. Such improved statistics will provide better input to the model and will effectively enable one to develop more accurate estimates of wind damage. The input requirements of the model will in turn identify those areas that lack and / or have problematic information and indicate the direction (and indicators) for possible improvements in the inspection programmes and data processing.

The current development process of the model has already allowed one to identify two important aspects of site inspections. The most relevant aspect is the necessity of capturing the spatial extent of wind damage events. This could be obtained from aerial surveys which are suitable for large regions with relatively low population densities. Alternatively, in regions with higher population densities, a comprehensive reporting procedure could be introduced, captured on a national or provincial level and combined with a GIS system. Such systems are in place in North America, Europe and South America (e.g. Argentina).

Another important issue is the introduction of uniform damage reporting standards and procedures at national level. Among other things, these should take into account the structural aspects of damage and the cost implications. In view of the large component of informal human development in South Africa, information on all types of amenities as well as the size of the affected communities should be included.

Figure 12.4: Schematic relationship between the model and full-scale wind damage data
Chapter 13
factors acting at their extreme values simultaneously is remote to the extent that it becomes negligible.

For this one would need to determine the maxima and arbitrary-point in-time distributions of the wind-related factors that contribute to the proposed model. (Such an undertaking would require a substantial amount of work, which is not feasible in the short to medium term.)

The maximum value of the combined wind-related factors can be expressed in terms of three combinations:

\[
W_{\text{max}} = \max \left\{ Z^{\text{max}} + F^{\text{apt}} + R^{\text{apt}}, Z^{\text{apt}} + F^{\text{max}} + R^{\text{apt}}, Z^{\text{apt}} + F^{\text{apt}} + R^{\text{max}} \right\}
\]

where Z, F and R refer to zones, footprints and rate of occurrence and the superscript \( ^{\text{max}} \) refers to maximum value within the specified period of time and \( ^{\text{apt}} \) refers to arbitrary point-in-time values of each factor.

Whichever combination of factors yields the largest \( W_{\text{max}} \) value, will be the controlling one to be used to calculate the maximum resultant coefficient of variation \( c_{\text{ov}}W \).

12.6 Re-evaluation of the model

An optimal way of assessing the principles, methodology and outputs of the proposed model would be to evaluate them against full-scale information on wind damage in South Africa. Such process could either be carried out retrospectively by re-visiting and re-processing the data on historical events or by an appropriate evaluation of future events. A general relationship between the proposed model and full-scale information on wind damage can be described schematically as shown in Figure 12.5.
This study describes the development of a wind damage model for disaster management purposes in South Africa.

The background information on global and South African wind disasters is presented, based on a comprehensive review of relevant international and local literature.

The role and relevance of wind loading codification is highlighted and this is followed by an analysis of factors that influence wind damage and, where relevant and possible, South African examples and research findings are presented.

In the course of the current project a database of wind damage / disaster in South Africa was set up and the results of the initial analysis of the data are included in the thesis.

The rationale for adopting the principles of spatial methodology for the proposed risk model is discussed. This is followed by the development of a generic algorithm to estimate the socio-economic implications of wind disaster and the wind speed probability of occurrence.

The wind climatic data that provides the three basic inputs required by the model, is subsequently discussed and developed namely:

- the geographic zones of dominant types of strong wind events,
- the generic footprints of strong wind events, and
- the rate of occurrence of various type of events.

Finally the application of the proposed model is demonstrated on the basis of a worked example.

Due to South Africa's complex climatic conditions, fairly drastic simplifications in characterising the properties of surface winds in various geographic regions were made. However, the model provides a useful and reasonable tool which utilises the limited data available to its maximum, and the next step enables one to use wind damage and disaster prediction to improve the process of data capture and analysis.

Further work is required to validate and increase the accuracy of the climatological aspects of the model. This could be carried out in an incremental manner, in which the starting point
would be the development of a dedicated GIS system linked to the database which has been developed in the course of the current project.

The information on the spatial extent of strong wind events (i.e. their footprints) forms the most critical component of the model. Further refinement of this information could be achieved through a combination of several activities including:

- further analysis and processing of the database on wind damage events,
- adequate survey and spatial analysis of future wind damage events,
- analysis and identification of the generic meteorological characteristics of climatic systems likely to develop into strong surface winds,
- correlation analysis of the sparse full-scale data, and
- application of relevant numerical modelling which quantifies the structure of various types of climatic events.

For the coastal strong wind events, the influence of topography on the wind speed distribution needs to be investigated. It is encouraging in this respect that negotiations are currently under way in which a substantial international funding could be applied to upgrading the weather recording facilities in the Eastern Cape in order to capture and study frontal weather passages and their impact on human built environment.

Also achievable within limited resources, would be to validate the information on the average number of occurrences per year of frontal / coastal wind events.

The information on human built development which is necessary includes:

- the correlation between the distribution of assets and development density (i.e. engineered structures vs. non-engineered, formal development vs. informal development), and
- the structural behaviour of the South African built environment, which will lead to
- the development of vulnerability curves.

The development of such data would necessitate setting up comprehensive programmes across the engineering professions, local authorities and insurance agencies. These should include development of a national framework of inspecting and documenting wind damage events and developing standard reporting procedures and methods of analysis, aimed at establishing the 'wind performance' of various types of amenities, which would lead to the development of vulnerability curves.
However, an initial step of developing a first approximation information would be to identify and quantify all relevant characteristics of representative cases of human built development. Such data could then be used for validation and further refinements of the model.

Due to its generic-spatial nature, the proposed model could be extended to include other types of devastation that are caused by natural events (e.g. hail, flood). A further possibility would be to develop a computer simulation linked to a real-time tracking system of strong wind events (e.g. coastal fronts or thunderstorms) to enable continuous monitoring and assessment of the geographic distribution of real-time risks and loss.
Chapter 14
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LIST OF FIGURES

Figure 2.1: Comparison of natural disasters
Figure 3.1a: Collapse of a garden wall (Rosettenville, Johannesburg, Oct. 1996)
Figure 3.1b: Overturned information sign; note the presence of bracing (Midrand, Sept. 2001)
Figure 3.1c: Minor damage to the fixing of roof sheeting (Umtata, Dec. 1998).
Figure 3.1d: Minor damage to roof tiling (Midrand, April 1994)
Figure 3.1e: Major damage to roof tiles and glazing; roof trusses and purlins largely intact (Welkom, March 1990)
Figure 3.1f: Entire roof sheeting pulled off and displaced; roof trusses intact (Rosettenville, Johannesburg 23 Oct. 1996).
Figure 3.1g: Portion of the roof totally removed (Uitenhage-Port Elizabeth, April 1993)
Figure 3.1h: Total destruction and removal of the roof, walls partially destroyed (Midrand, April 1994)
Figure 3.1i: Serious damage to roof and walls (Welkom, March 1990).
Figure 3.1j: Total devastation of the second floor of residential flats (Mannenberg-Cape Flats, Aug. 1999)
Figure 3.1k: Lightweight roof totally removed and collapse of large-span wall (Matsulu, July 1992)
Figure 3.1l: Foundations and toilet units – the only reminder of a lightweight pavilion which was blown away; note that the adjacent structure of similar construction escaped with the loss of the roof only (Piet Retief, Dec. 1986)
Figure 3.1m: Debris from aircraft hangars (Harrismith, Nov. 1998)
Figure 3.1n: Grandstand of a stadium (Piet Retief, Dec. 1986)
Figure 3.1o: A telephone pole which has snapped (Heidelberg, Oct. 1999)
Figure 3.1p: Damage to external sheeting of an industrial structure (Centurion, Oct. 1999)
Figure 3.1q: 110 kW power line toppled (Welkom, March 1990)
Figure 3.1r: Several parallel power lines (Welkom, March 1990)
Figure 3.2a: Footprint of windstorm damage in Prieska (3 December 1960)
Figure 3.2b: Footprint of Welkom tornado (20 March 1990)
Figure 3.2c: Footprint of a microburst in Rosendal (20 April 1994)
Figure 3.2d: Tornadic trail of damage in Centurion (21 Oct. 1999)
Figure 3.3a: A steel telephone pole bent but not overturned; note no debris which could have assisted in deformation was found at the site (Heidelberg, Oct. 1999)
Figure 3.3b: Corrugated steel sheeting wrapped around a tree (Welkom, March 1990)
Figure 3.3c: Bent street light (Cape Flats, Aug. 1999)
Figure 3.3d: Bent road-sign (Welkom, March 1990)
Figure 3.3e: A telephone pole twisted at its base (Utrecht, Nov. 1993)
Figure 3.3f: Collapse of two perpendicular sections of a free-standing 220mm brick wall (Umtata, Dec. 1998)

Figure 3.3g: A 4 ton harvester which has been lifted and carried about 500 m (Utrecht, Nov. 1993)

Figure 3.3h: The suspended ceiling of a foyer which was sucked out despite substantial protection offered by a concrete parapet beam connected to the column (Midrand, Sept. 2001)

Figure 3.3i: A wire fence flattened by a tornado (Utrecht, Nov. 1993)

Figure 3.3j: A temporary fence overturned by south-easterly winds (Cape Town, August 1997)

Figure 3.4: Losses due to wind disasters in the USA

Figure 3.5a: Idealised vulnerability curve for fully-engineered structures

Figure 3.5b: Schematic graphs of hurricane vulnerability for commercial buildings in the USA

Figure 3.5c: Schematic graphs of hurricane vulnerability for commercial buildings in Puerto Rico

Figure 3.5d: Schematic graphs of vulnerability obtained from an analysis of winter storms in Europe

Figure 3.6: Mean rate of occurrence of tornadoes in South Africa

Figure 3.7: Generic footprint of a European winter storm (note the contours of the UK, France etc.)

Figure 3.8a: Range of relative grades for different building categories

Figure 3.8b: Parameters for knowledge based system

Figure 3.9: Typical informal shelter assembled from metal sheeting

Figure 3.10a: Failure of roof and damage to walls caused by inadequate roof ties (Piet Retief, December 1986)

Figure 3.10b: Failure of roof and damage to gable wall caused by inadequate roof ties (Cape Flats, August 1999)

Figure 3.10c: Entire roof and top row of bricks torn off and removed (Matsulu – July 1992)

Figure 3.11: Devastation of a garage (Welkom, March 1990)

Figure 3.12a: Collapse of unsupported walls in formal housing (Matsulu, July 1992)

Figure 3.12b: Collapse of unsupported wall of informal house (Bethany-Drakensberg, Dec. 1997)

Figure 5.1: Down-slope mountain wind

Figure 5.2: Regional basic wind speeds for South Africa

Figure 5.3a: Record of extreme wind speed (Fort Beaufort 25 Feb. 2000)

Figure 5.3b: Two time traces of thunderstorms with a leader-gusts

Figure 5.3c: Extreme wind speed due to a microburst

Figure 5.4: Maximum mean hourly wind speeds for South Africa

Figure 5.5: Time history of pressure caused by a frontal cyclone (Strand, 29 Aug. 1999)
Figure 5.6: Time trace of a typical South-Easter (Cape Town International Airport, 2 March 1994)
Figure 5.7: Probability distribution of mean and gust wind speeds for Cape Town International Airport
Figure 5.8: Geographical distribution of tornado events, 1905-1997
Figure 5.9: Climatologically homogenous regions for the study of severe thunderstorm occurrences in the USA
Figure 5.10: Wind roses for South Africa
Figure 5.11a: Profiles of selected wind quantities affected by a dominant topography
Figure 5.11b: Directional distribution of local winds in the lee of dominant topography
Figure 5.12a: Directions of local winds at the base of a tall building
Figure 5.12b: Probabilities of wind speed occurrence at two locations within a city environment
Figure 5.13: Idealised schematic comparison of wind vulnerability of engineered and non-engineered structures
Figure 5.14: A typical informal development
Figure 5.15: Analysis of approaching terrain / wind conditions
Figure 5.16a: Layout of Brink's Vlakfontein township (1992) (based on photo-interpretation)
Figure 5.16b: Layout of Brink's Vlakfontein township (1996) (based on photo-interpretation)
Figure 5.17a: Traditional housing unit – rondavel
Figure 5.17b: A rondavel escaped unscathed while the neighbouring rectangular-shaped structures were destroyed (Bethany, Eastern Cape, Dec. 1997)
Figure 5.18a: Edge roof tiles removed by wind (Bellville, Dec. 1996)
Figure 5.18b: Minor damage to a thatched roof (Midrand, April 1994)
Figure 5.18c: Damage to the roof sheeting of a large commercial building
Figure 5.18d: A missing portion of sheeting of a large-span roof due to wind action
Figure 5.19: Traditional method of preventing roof uplift
Figure 5.20: Plan of a core housing unit
Figure 5.21a: Wind devastation of a pre-engineered housing unit (Matsulu, July 1992)
Figure 5.21b: Additional stiffening pillar to support a large gable wall
Figure 5.22: A collapsed floodlight mast (Matsulu, July 1992)
Figure 5.23: Damaged reinforced concrete element (Bronkhorstspruit, May 1949)
Figure 5.24: Devastation of Albertynsville (Nov. 1952)
Figure 5.25: An airborne shed which landed on a car (Cape Town, date unknown)
Figure 5.26: Roof sheet debris entangled in power line conductors
Figure 5.27: Relationship between particle size and threshold wind speed of uplift
Figure 5.28a: Structural damage due to wind undermining foundations (Cape Flats)
Figure 5.28b: Unwanted deposition of sand (Cape Flats)
Figure 5.29a: Simulated erosion pattern between buildings
Figure 5.29b: Analysis of the extent of erosion
Figure 6.1a: Sample form - Wind Damage Database (thunderstorm event)
Figure 6.1b: Sample form - Wind Damage Database (tornado event)
Figure 6.2a: Annual distribution of wind damage events
Figure 6.2b: Monthly distribution of damaging events
Figure 6.2c: Life and limb consequences of strong wind events
Figure 6.2d: Reports of damage to various types of structures
Figure 6.2e: Number of homeless people
Figure 7.1: Weather recording stations
Figure 7.2a: Comparison of areas
Figure 7.2b: Number of recording stations
Figure 7.3: Climatic regions of South Africa
Figure 7.4: Schematic flowchart of the model
Figure 7.5: Generic footprint of a strong wind event type W, over a Region A
Figure 7.6: Areas subject to ranges of wind speeds
Figure 7.7: Rate of occurrence of wind speeds exceeding the threshold ranges per unit area per year in Region A
Figure 7.8: Developed settlements $S_j$ within Region A
Figure 7.9: Developed areas subject to ranges of wind speeds
Figure 7.10: Rate of occurrence of wind speeds exceeding the threshold ranges per unit area per year over developed settlements within Region A
Figure 7.11a: Densities of development within settlement $S_j$
Figure 7.11b: Distribution of asset values in settlement $S_j$
Figure 7.12: Total area for each development asset value exposed to threshold levels of wind speed
Figure 7.13: Generic vulnerability curves
Figure 7.14: Diagram of the process
Figure 8.1: Zones of strong wind events in South Africa
Figure 8.2: Overlaps between the zones of strong wind occurrence
Figure 9.1: Radar reflectivity layouts of thunderstorms: a) weak to moderate, b) strong and c) intense
Figure 9.2: Radar reflectivity image of a thunderstorm (Irene, 12 September 2001)
Figure 9.3: Comparison of wind speeds and radar reflectivity: a) Bethlehem, 28 November 1995, b) Bloemfontein, 4 November 2000
Figure 9.4: Comparison of reflectivity index and gust wind speeds
Figure 9.5: Generic footprints of wind speeds in thunderstorm: a) weak to moderate, b) strong and c) intense
Figure 9.6: The extent of areas subject to strong winds
Figure 9.7: Footprint of a downburst
Figure 9.8: Frequency distribution of storm lifetimes
Figure 10.1: Map of population density
Figure 10.2: Distribution of income per capita
Figure 10.3: Distribution of informal housing
Figure 10.4: South African major electricity grid
Figure 10.5: Distribution of major urban nodes and dense settlements
Figure 10.6: Accumulation Assessment Zones
Figure 11.1: Vanderbijlpark Magisterial District: land use cover
Figure 11.2: Vanderbijlpark Magisterial District: population distribution
Figure 11.3: Total number of km² subject to threshold wind speeds
Figure 11.4: Rate of occurrence of wind speeds larger than the threshold levels
Figure 11.5: Total exposure area in km² for each development asset value exposed to threshold levels of wind speeds
Figure 11.6: Proposed vulnerability curves for asset values m₁ – m₄
Figure 11.7: Average accumulated loss per km² per year for each asset value
Figure 12.1: Uncertainties in the extent of a zone
Figure 12.2: Reflectivity vs. peak gust wind speed
Figure 12.3: Statistical 'wind input' factors
Figure 12.4: Schematic relationship between the model and full-scale wind damage data
APPENDIX B

LIST OF TABLES

Table 2.1: Contribution of windstorm disasters (as a percentage of loss due to all natural hazards in the USA)
Table 3.1a: Definition of damage index for a house
Table 3.1b: Factors affecting the strength of houses
Table 3.1c: Classification of basic house structures
Table 5.1: Fujita / Pearson Tornado Scale (after Fujita [1973])
Table 9.1: Matrices of width \( w_{ki} \) and length \( l_{ki} \), (km) in terms of wind speeds and storm classification
Table 9.2: Matrix of generic areas (footprints) (km\(^2\)) in terms of wind speeds and storm classification
Table 9.3: Generic areas and rates of occurrence
Table 9.4: Summary of information on strong wind events
Table 11.1: Total number of km\(^2\) exposed to ranges of wind speeds
Table 11.2: Probabilities of threshold wind speeds striking a km\(^2\) of an asset density
Table 11.3: Total exposure area in km\(^2\) subject to various threshold wind speeds
Table 11.4: Total exposure area in km\(^2\) subject to ranges of wind speeds
Table 11.5: Number of people affected
Table 11.6: Damage as a percentage of total asset value
Table 11.7: Accumulated loss per km\(^2\) (in Rm)
Table 11.8: The average loss per year (in Rm)
Table 12.1: Ranges of proposed coefficients of variation
Table 12.2: Mean and root-mean-squares of data series