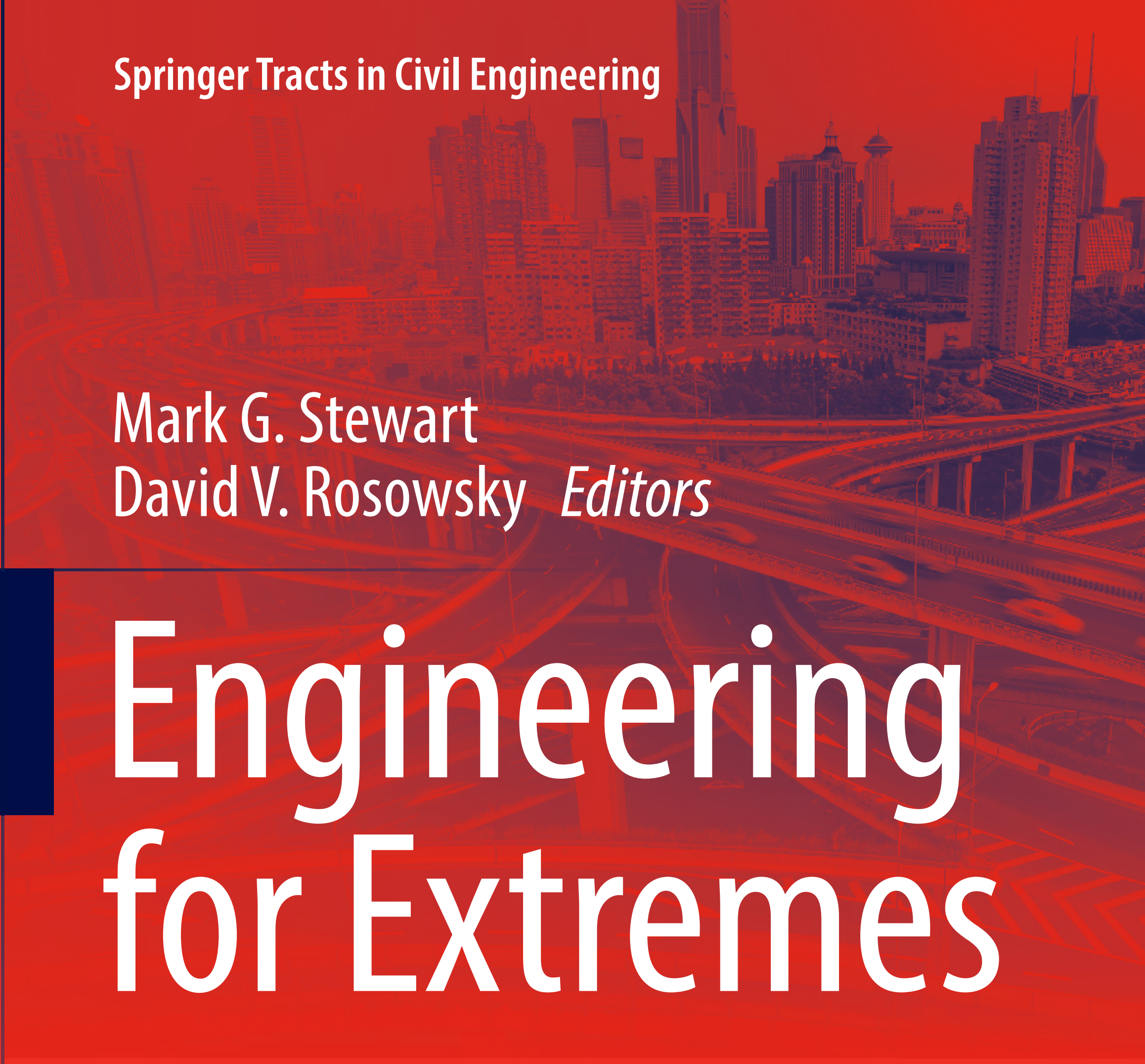

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Mark G. Stewart
David V. Rosowsky *Editors*

Engineering for Extremes

Decision-Making in an Uncertain World

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Editors

Engineering for Extremes

Decision-Making in an Uncertain World

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Preface

The community has always been worried by extreme weather events and for good reason. In the era before insurance, the personal and financial loss from a flood, storm, fire, hurricane, or earthquake could wreck livelihoods, destroy homes, shops and workplaces, and lead to widespread poverty and destitution that might take generations to recover from. While these devastating consequences are often avoided in the developed world, they remain a sad reality for much of the world.

It is therefore of no surprise that the civil engineering profession has its roots in improving the resilience of the community to extreme events. The desire to build a flood proof river crossing led to the revolutionary cast-iron Iron Bridge being built in Coalbrookdale in England in 1779 for what in its day was an impressive 30 m span. Within a century, civil engineering had advanced to the point where spans of 500 m or longer were possible—the Brooklyn Bridge linking the communities of Manhattan and Brooklyn in New York City being one notable example.

Despite this progress, significant challenges remain today. Buildings, bridges, roads, nuclear power plants, and other infrastructure essential to our economic and social well-being are at an increasing risk from terrorism, climate change, hurricanes, storms, floods, earthquakes, heat waves, fires, and other extreme events. The timing and severity of these extremes are highly uncertain and are characterised as low probability–high consequence events. Risk and cost–benefit analyses of protective measures aim to reduce the vulnerability of infrastructure and hence reduce the future impact of extreme events to reveal protective measures that are cost effective and those that are not. Relevant also are private and public policy imperatives in the decision-making process.

Extreme events and actions taken to reduce the vulnerability of infrastructure are sometimes based on worst-case thinking, probability and cost neglect, and risk aversion. This can result in a frightened public, costly policy outcomes, and wasteful expenditures.

The book will explain how risk and decision-making analytics can be applied to the wicked problem of protecting infrastructure and society from extreme events. There is increasing research that takes into account the risks associated with the timing and severity of extreme events in engineering to reduce the vulnerability or increasing the resiliency of infrastructure—we refer to this as ‘*Engineering for Extremes*’. Engineering for extremes is defined as measures taken to reduce the vulnerability or increase the resiliency of built infrastructure to climate change, hurricanes, storms, floods, earthquakes, heat waves, fires, and malevolent and abnormal events that include terrorism, accidental explosion or fire, vehicle impact, and vehicle overload. This may include, for example, enhancement of design standards (higher design loads or flood levels), retrofitting or strengthening of existing structures, utilisation of new materials, and changes to inspection and maintenance regimes.

The book will introduce the key concepts needed to assess the economic and social well-being risks, costs, and benefits of infrastructure to extreme events. This will include hazard modelling (likelihood and severity), infrastructure vulnerability, resilience or exposure (likelihood and extent of damage), social and economic loss models, risk reduction from protective measures, and decision theory (cost–benefit and utility analyses). This will be followed by case studies authored by experts from Australia, USA, Canada, UK, Ireland, France, New Zealand, China, Japan, South Africa, and South America. These case studies will describe succinctly the practical aspects of risk assessment when deciding on the most cost-efficient measures to reduce infrastructure vulnerability to extreme events for housing, buildings, bridges, roads, tunnels, pipelines, and electricity infrastructure in the developed and developing worlds.

The editors have been colleagues and close friends for nearly 30 years. One introduced the other to a lifetime addiction to Dunkin Donuts and the other to the delights of an Aussie favourite—Tim Tams. This book became our COVID project. It was also an excuse to reach out to our friends and colleagues around the globe. Their response to our book proposal was warm and generous. All the more so as, we were all battling the personal trauma and professional disruptions wreaked by COVID-19. In these trying times, their support was something we will not easily forget.

So we are incredibly grateful to the authors of the chapters. The authors shared our enthusiasm for the book and, more importantly, devoted much time and energy to producing chapters that are at the forefront of the latest developments, are engaging to a non-specialist reader, and provide a focus on practical decision outcomes. The chapters reflect the expertise of the authors and the latest developments on engineering for extremes.

Finally, we appreciate the support from the folks at Springer in bringing this book to fruition.

Newcastle, Australia
Kansas, USA
May 2021

Mark G. Stewart
David V. Rosowsky

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Part III Case Studies

Part IV Conclusions and Recommendations

About the Editors

Mark G. Stewart is Professor of Civil Engineering and Director of the Centre for Infrastructure Performance and Reliability at The University of Newcastle in Australia. Professor Stewart is an international leader in risk assessment, public policy decision-making, and protective infrastructure for extreme hazards. He is Author of *Probabilistic Risk Assessment of Engineering Systems* (Chapman & Hall 1997), *Terror, Security, and Money: Balancing the Risks, Benefits, and Costs of Homeland Security* (Oxford University Press 2011), *Chasing Ghosts: The Policing of Terrorism* (Oxford University Press 2016), *Are We Safe Enough? Measuring and Assessing Aviation Security* (Elsevier 2018), an edited book *Climate Adaptation Engineering: Risks and Economics for Infrastructure Decision-making* (Elsevier 2019), as well as more than 500 technical papers and reports. He has more than 30 years of experience in probabilistic risk and vulnerability assessment of infrastructure and security systems that are subject to man-made and natural hazards. He has attracted more than $10 million in research funding. In the past decade, Stewart has led the way in risk-based assessment of terrorism and climate change impacts on engineering infrastructure with 25 keynotes at international conferences. He is Editor-in-Chief of *Structural Safety* and Fellow of the Australian Academy of Technology and Engineering.

David V. Rosowsky is Vice President for Research at Kansas State University where he also holds the title of Professor of Civil Engineering. Prior to joining K-State, he served for six years as Provost and Senior Vice President and Provost at University of Vermont. Prior to that, he served as Dean of Engineering at Rensselaer Polytechnic Institute and before that as Head of the Zachry Department of Civil Engineering at Texas A&M University where he also held the A.P. and Florence Wiley Chair in Civil Engineering. He also previously held Richardson Chair in Wood Engineering and Mechanics at Oregon State University and was Faculty Member at Clemson University. Since 1990, he has conducted research in the areas of structural reliability, performance of wood structural systems, design for natural hazards, stochastic modelling of structural and environmental loads, and probability-based codified design. His current research addresses three topics: (1) behaviour of the built environment subject to natural hazards, most recently including the effects of climate change and adaptation, (2) modelling and analysis of load effects on buildings and other structures with particular emphasis on complex environmental phenomena, and (3) performance-based engineering for design, post-disaster condition assessment, and loss estimation studies. He has authored or co-authored more than 300 technical papers. A recognised expert in the field of structural reliability, he has been invited to present his research work around the world including invited lecturers in France, Italy, Switzerland, Canada, Japan, Australia, and New Zealand. He has supervised more than 20 masters and doctoral students. He is Recipient of the ASCE Walter L. Huber Research Prize, the T. K. Hseih Award from the Institution of Civil Engineers (UK), and the ASCE Norman Medal.

Part I
Introduction

Chapter 1
Extreme Events for Infrastructure: Uncertainty and Risk

Mark G. Stewart and David V. Rosowsky

Abstract Buildings, bridges, roads, and other infrastructure essential to our economic and social well-being are at an increasing risk from hurricanes, storms, floods, earthquakes, tsunamis, heat waves, fires, terrorism, climate change and other extreme events. The timing, severity and combination of these extremes are highly uncertain, and are characterised as low probability-high consequence events. The chapter starts by introducing and reviewing basic concepts about risk and cost–benefit analysis of protective measures aim to reduce the vulnerability of infrastructure, and hence reduce the future impacts of extreme events to reveal protective measures that are cost-effective, and those that are not. This literature review justifies the introduction of risk-based decision support that integrates hazard, engineering, and fragility models, as well as economical decision tools to perform a comprehensive assessment of the cost-effectiveness of protective measures. This risk-based decision support will be illustrated with various study cases of engineering for extremes in the following chapters of this book.

Keywords Risk · Decision making · Infrastructure · Extreme events · Hazard · Safety · Cost–benefit analysis · Uncertainty

1.1 Introduction

Buildings, bridges, roads, and other infrastructure essential to our economic and social well-being are at an increasing risk from hurricanes, storms, floods, earthquakes, tsunamis, heat waves, fires, terrorism, climate change and other extreme events. The timing and severity of these extremes are highly uncertain, and are characterised as low probability-high consequence events.

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Extreme events arouse much fear and anxiety in society. And for good reason. The terrorist attacks on 11 September 2001 killed nearly 3000 people in New York and Washington, caused $250 billion in loss of life, infrastructure damage, loss of tourism, reduction in GDP and other direct, indirect and social losses [31]. Since then, over $2 trillion has been spent by the United States on domestic counter-terrorism, and much more on the wars in Afghanistan, Iraq and Syria [33]. The World Bank reports that losses in the built environment from extreme climate hazards are over $300 billion per year, and can rise to $415 billion by 2030 [65], see also Fig. 1.1. Climate change will add to these losses, with the World Bank estimating that sea-level rise and subsidence in the 136 largest coastal cities could result in losses of up to $1 trillion per year by 2050 without further investment in adaptation and risk management. Figure 1.2 shows that fatalities from natural disasters can exceed 300,000 in any one year, and the long-term average is about 100,000 deaths per year. Figure 1.3 shows that the vast majority of losses and fatalities arise from natural disasters (floods, storms, earthquakes, droughts/forest fires/heat waves, cold waves/frost, hail, tsunamis) as these tend to cause widespread damage to large communities or regions. On the other hand, man-made disasters (major fires and explosions, aviation and space disasters, shipping disasters, rail disasters, mining accidents, collapse of buildings/bridges, and terrorism) tend to affect a large object in a very limited space resulting in lower losses when compared to natural disasters. Extreme events, such as climate change, are also deemed by some to be direct threats to national security (e.g., [52]).

While these are staggering losses, they can be ameliorated with targeted strategies to reduce vulnerability, increase resilience or reduce exposure of infrastructure and people to extreme events. For example, the World Bank shows that the net benefit of building more resilient infrastructure in low and middle income countries would be

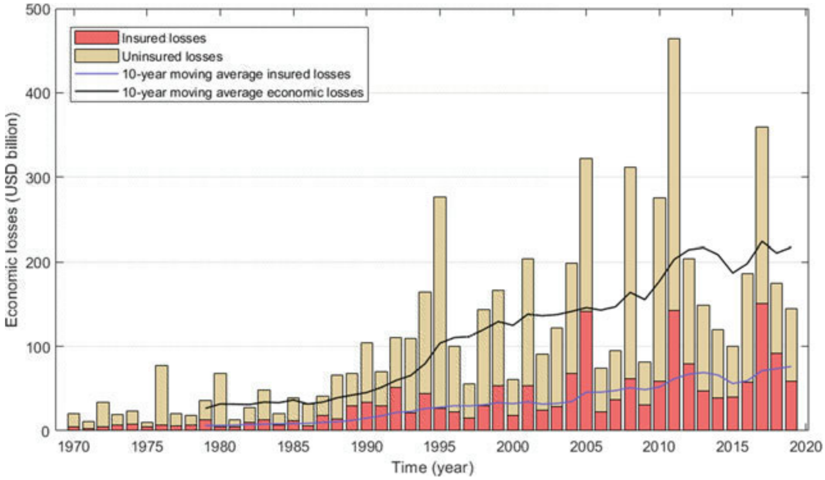

Fig. 1.1 Losses from extreme events (adapted from Swiss Re [58])

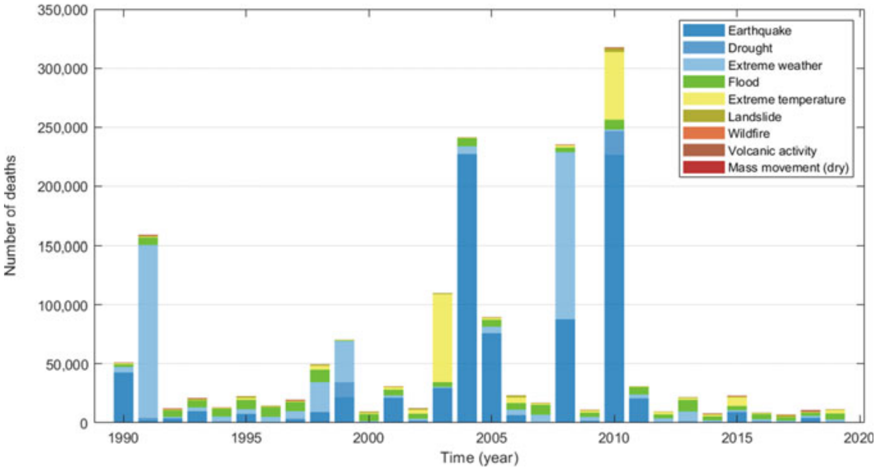

Fig. 1.2 Number of fatalities based on disaster type (adapted from OWD [39])

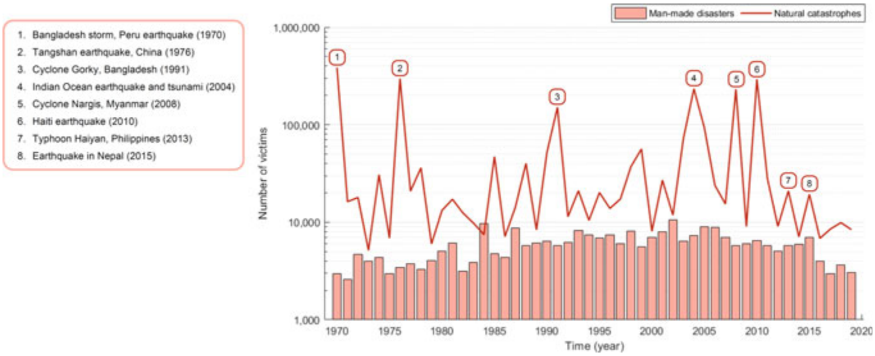

Fig. 1.3 Number of victims from extreme events (adapted from Swiss Re [58])

$4.2 trillion with $4 of benefit for every $1 invested—i.e. a benefit-to-cost ratio of 4 [15].

There are countless examples where governments can invest wisely in infrastructure programs that provide net lifesaving and economics benefits to society. One is a $27 billion flood protection system for New Orleans that would reap benefits of more than $35 billion, including saving more than 1000 lives [13]. Another is reduced vulnerability of a key airport road to flooding may be achieved by the installation of two additional culverts at a cost of $1.7 million, a risk-based analysis showed a net benefit of $11 million with a benefit-to-cost ratio of 7.3—i.e., $1 of cost buys $7.30 in benefits [35].

It follows that the emphasis of the book is built infrastructure, most notably, housing, buildings, bridges, roads, tunnels, pipelines, and electricity infrastructure in the developed and developing worlds. This accords with the World Bank [66] for the need for the “construction of buildings, infrastructure, and urban developments should consider how design, construction practices, and construction materials will affect disaster risk in both current and future climates.” Risk and cost–benefit analysis of risk mitigation or protective measures aim to reduce the vulnerability of infrastructure, and hence reduce the future impact of extreme events to reveal protective measures that are cost-effective, and those that are not. Relevant also are private and public policy imperatives in the decision-making process.

The focus of this chapter (and this book) is how risk and decision-making analytics can be applied to the complex problem of protecting infrastructure and society from extreme events. There is increasing research that takes into account the risks associated with the timing and severity of extreme events in engineering to reduce the vulnerability or increase the resiliency of infrastructure—we refer to this as ‘*engineering for extremes*’. Engineering for extremes is defined as measures taken to reduce the vulnerability or increase the resiliency of built infrastructure to climate change, hurricanes, storms, floods, earthquakes, heat waves, fires, and malevolent and abnormal events that include terrorism, gas explosions, vehicle impact and vehicle overload. This may include, for example, enhancement of design standards (higher design loads or flood levels), retrofitting or strengthening of existing structures, utilisation of new materials, and changes to inspection and maintenance regimes. Engineers have a unique responsibility to model infrastructure vulnerability, and these skills will be essential to modelling the impacts of extreme events, and measures to ameliorate these losses.

Engineering for extremes involves quantifying the risks, costs and benefits of infrastructure protection and resilience. Any measures need to be economically and socially viable. There are also uncertainties, risks, upsides, and downsides that need to be factored into any decision. And we are talking about decisions that will involve many hundreds of billions of dollars of expenditures—so there is a need to explore the full range of options to effectively compare costs and benefits. There is no certainty about the future which makes decision-making for extreme events, even those as yet unforeseen or unrecognized, challenging. There is clearly a need for action, the question is what should we be doing now? what decisions can be deferred? and to when? And perhaps most importantly—what information do we need to enable better decisions?

The chapter will describe how risk-based decision support is well suited to optimising the design, construction, operation and maintenance of built infrastructure. Stochastic methods are used to model infrastructure vulnerability, effectiveness of risk mitigation or protective strategies, exposure, and costs. Case studies to follow in other chapters will detail how state-of-the-art risk-based approaches will help ’future proof’ built infrastructure to extreme events.

The book will introduce the key concepts needed to assess the economic and social well-being risks, costs and benefits of infrastructure to extreme events. This will include: hazard modelling (likelihood and severity), infrastructure vulnerability, resilience or exposure (likelihood and extent of damage), social and economic loss models, risk reduction from protective measures, and decision theory (cost–benefit and utility analyses).

1.2 Engineering for Extremes

The design and construction of infrastructure has evolved over many millennia so that today we are able to predict with relative ease the likelihood and size of today's natural hazards, and take steps to design houses, buildings, bridges, power stations, dams and other infrastructure to withstand these anticipated hazards. Earthquakes, tropical cyclones or hurricanes, storm surge, floods, and blizzards are often the low probability—high consequence hazards of interest. Over the past century building standards have been developed and continually improved—with the prevention of building collapse and catastrophic loss (ultimate limit state) the main driver for change. And while uncertainties and knowledge gaps still exist, disaster risks in the developed world are, in general, at an acceptable level. This is particularly the case for life-safety risks where, for example, the annual fatality rate from earthquakes in New Zealand is close to the generally acceptable risk of 1×10^{-6} or one in a million (e.g. [49, 59]). However, the seismic fatality rate in China in the decade 2001 to 2010 is 50 times higher at 5×10^{-5} (data sourced from Li et al. [27]).

Often the huge loss of life in the developing world is due to the poor quality of construction [48]. In Bangladesh, the quality of cement is poor [26]. And in Turkey, higher than expected earthquake damage is attributed to project errors, poor quality of construction, unlicensed modifications to buildings, and so on [22]. A magnitude 7.0 earthquake in Haiti in 2010 killed more than 230,000 people, mainly because of poor building construction, whereas a larger earthquake in densely populated Kobe, Japan, in 1995 killed around 6000, and a magnitude 6.9 earthquake in 1989 in the San Francisco Bay area killed some 63 people. Surveying the damage caused by an earthquake in China in 2008, in which many schools collapsed, killing hundreds of children, a field team of Australian and Hong Kong earthquake experts observed that "many buildings had inadequate construction quality including insufficient reinforcement, poor detailing and poor quality concrete" [63]. In addition, building codes have been bypassed with the complicity of corrupted officials and construction site staff. As Penny Green notes for Turkey, "Violations were part of a well entrenched political process," and she quotes an adviser to the mayor in one of the worst hit earthquake areas of Turkey, who admits, "The project managers, they take bribes, we do it ourselves. There is no project inspection" [10].

On the other hand, large economic losses often arise from natural disasters in the developed world. For example, in 2012 Hurricane Sandy (also known as 'Superstorm Sandy') damaged over 750,000 residences in New Jersey and New York, and caused more than $50 billion in losses [20]. Loss of life numbered around 100, mostly from drownings. The 2010–2011 earthquakes in Christchurch killed 185 people, most of these were victims of the collapse of two multi-storey buildings, and caused over $30 billion in damages—or 20% of the New Zealand GDP. The widespread damage across the CBD and suburbs led to over 750,000 insurance claims being lodged, 64% of businesses were forced to close temporarily, and 11% were forced to close permanently [42]. With the exception of two buildings that collapsed, other buildings performed as expected and did not collapse—so life-safety was ensured. However, the widespread damage to building reduced their functionality and this loss was the main contributor to the huge economic losses suffered by the New Zealand economy, and to the massive social dislocation of residents.

A key emphasis of this book is to reduce damage to infrastructure that in turn can ameliorate the social and economic disruption of extreme events to the built environment. It aims to provide practical and community-conscious engineering knowledge and solutions to reduce the impact of extreme events on the performance of buildings and infrastructure, including safety, serviceability, and durability. Examples to be presented in this book include:

- installing wind-rated windows to houses to reduce damage from extreme wind events,
- replacing timber power poles with steel or concrete poles to reduce vulnerability to hurricanes,
- installation of additions jet fans for providing mechanical ventilation to reduce fatality risks during a fire in a tunnel,
- use of blast walls and fences to reduce the effects of explosive blast loading,
- construction of a new road to increase the resilience of vulnerable communities to earthquakes, storms and tsunami,
- upgrading building energy efficiency ratings for houses using insulation, sealing, and phase change materials to reduce heat stress during heatwaves,
- increasing foundation depth for bridges to reduce risks of scouring and bridge collapse during extreme floods,
- upgrading construction quality and practices to increase housing resilience,
- and so on.

1.3 Decision Challenges for Extreme Events

Cyclones, earthquakes, tsunami and floods are natural hazards that cause significant human, economic and social losses. Added to this are ‘man-made’ hazards such as climate change and terrorism. These hazards are low probability—high consequence events which in recent times are more commonly referred to as ‘extreme events’. Extreme events illicit extreme reactions—risk aversion, probability neglect, cost neglect, worst-case thinking—that may distort the decision-making process in an effort by policy makers to be seen to be ‘doing something’ irrespective of the actual risks involved. Policy-making in these circumstances becomes a “risky business” [17]. If rational approaches to public policy making are not utilised, then politically driven processes “may lead to raising unnecessary fears, wasting scarce resources, or ignoring important problems” [40].

There are a number of issues and questions related to controversial and emotive issues such as terrorism, nuclear power plant accidents, climate change and other extreme events [31–33], and are discussed as follows.

1.3.1 Worst-Case Thinking

Worst-case thinking, or hyperbole, tends to dominate the thinking of many terrorism and climate change experts. In 2008, Department of Homeland Security (DHS) Secretary, Michael Chertoff proclaimed the "struggle" against terrorism to be a "significant existential" one [31]. And in 2014, Mayor Bill de Blasio of New York at a U.N. summit proclaimed that "We know humanity is facing an existential threat" from climate change [11]. The notion that a threat short of all-out nuclear war could be existential to humanity is hard to fathom. If business as usual predictions are biased towards impending doom, then this justifies any response no matter the cost in loss of civil liberties, quality of life, and treasure.

1.3.2 Cost Neglect

While it is not difficult to list hazards and vulnerabilities, what is more challenging is to ascertain the cost to reduce these hazards and vulnerabilities. And to decide who pays, and when. There is a notion that safety is infinitely good, and no cost is too high. There is no attempt to compare costs against benefits.

1.3.3 Probability Neglect

Some analysts base their findings on hazards or scenarios that they assume will occur. There is no consideration of the likelihood that a specific CO_2 emission scenario will occur, or that mitigation or adaptation will be effective. For example, a U.S. 2014 climate risk assessment report predicts trillions in dollars of damage due to climate change for the business as usual scenario—i.e., the U.S. continues in its current path [46]. There is no attempt to quantify the likelihood that CO_2 emissions will continue unabated for the next 85 years, that CO_2 mitigation measures will be implemented, that adaptation measures are implemented, or the impact of improved or game-changing technologies. Sunstein [57] terms this as 'probability neglect' and that "people's attention is focused on the bad outcome itself, and they are inattentive to the fact that it is unlikely to occur." There is no certainty with predictions, nicely summed up by physicist Niels Bohr: "Prediction is very difficult, especially if it's about the future."

1.3.4 Opportunity Costs

Policy-makers that act before they carefully consider the implications of their actions can result in undesirable outcomes which are often referred to as 'opportunity costs'. A CO_2 mitigation strategy that reduces economic growth, particularly in developing countries, may reduce their ability to adapt. Or tsunami barriers may have a detrimental effect on tourism and the amenity for the local community.

1.3.5 Acceptable Risk

The notion of acceptable risk is rarely raised in public discussions. The world is not risk free. The generally accepted level of annual fatality risk is 1 in a million (e.g. Stewart and Melchers [49]), see, for example, Gardoni and Murphy [8] for a fuller discussion on risk acceptability. The probability that an American will be killed by a hurricane stands at about one in 7 million per year, and one in 2.8 million per year for a heat-related death [36]. By comparison, an American's chance of being killed in an automobile crash is about one in 9,500 a year, the chance of being a victim of homicide is about one in 20,000, and the chance of being killed by lightning is one in 10 million [53]. The chance of being killed in a natural disaster in the United States is a relatively high one in 500,000 per year [53]. How much should we be willing to reduce a risk, and is the risk reduction worth the cost?

1.4 Risk-Based Decision Support

Risk is a measure of expected loss, and quantifies the effect of uncertainty on factors that influence this loss. The standard definition of risk is:

$$(\text{Risk}) = (\text{Hazard}) \times (\text{Vulnerability}) \times (\text{Consequences}) \tag{1.1}$$

The nomenclature can vary from discipline to discipline, but in the context of built infrastructure, these terms are defined as:

1. Hazard—the likelihood and location of a natural or man-made hazard.
2. Vulnerability—how will the infrastructure be damaged?
3. Consequences—what is the life-safety, economic and social costs if the infrastructure is damaged? The criticality of the consequences will depend on the exposure—e.g., the time of day, the location of damage, exposed population, etc.

A risk assessment will combine these three measures in a way to estimate the overall risk to people, operations and infrastructure. The risk assessment process adopted by the International Organization for Standardization *Risk Management* ISO 31000–2018 is shown in Fig. 1.4.

A number of steps are basic to a risk assessment, and they are independent of the system or issue being considered. The process shown in Fig. 1.5 is also consistent with [23] and can be summarised as [49]:

1. **Define context.** A risk assessment should take place within a well-defined context. This means that the system being examined and the internal and external influences must be known and defined.
2. **Analyse hazard scenarios.** Identification of what might go wrong—and when and where—are crucial to the analysis. Once the potential hazards and scenarios have been identified, it is necessary to identify how and why these threats or scenarios can be realised. It requires the hazard scenarios to be examined (and understood) in considerable detail. Information from databases and other past experience will play an important part in hazard scenario analysis.
3. **Analyse risk.**

$$\text{RISK} = (\text{probability of occurrence}) \times (\text{consequences})$$

This is concerned with determining the occurrence probabilities and the consequences (fatalities, injuries, damages) that would occur if the threat or hazard were realised. Typically, the probabilities are estimated from a combination of relevant data, reliability modelling, and subjective judgments .

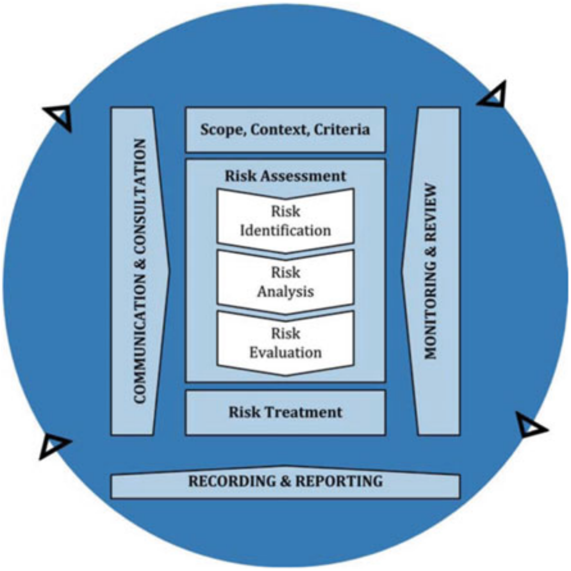

Fig. 1.4 Risk process (adapted from [23])

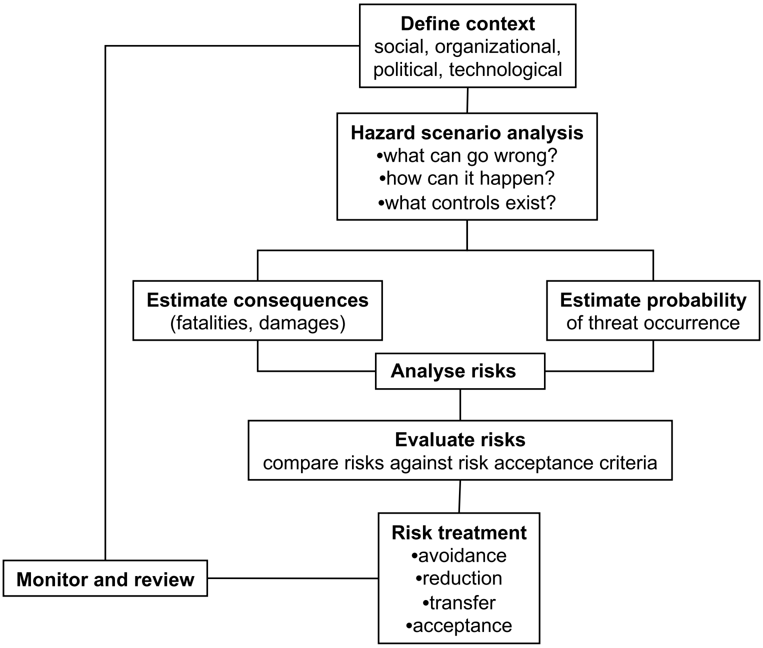

Fig. 1.5 Risk assessment process [49]

4. **Evaluate risks.**
   Analysed risk must be compared with criteria of risk acceptability, usually applying past experience as a guide.
5. **Treat the risk.**
   If the estimated risk exceeds the risk acceptance criteria, risk treatment is required. This may involve risk avoidance, risk reduction, risk transfer, or risk sharing. In some cases, the risk may be accepted but perhaps only for a limited time until measures can be taken to reduce it. In all cases, the proposed course of action requires careful evaluation. Consideration must be given to possible options and to the likely effect of their implementation, such as opportunity costs. This might involve one or more new risk analyses to gauge the effect of changes.
6. **Monitor and review.**
   Usually a risk analysis presents only a snapshot of the risks—for example, the effectiveness of control procedures may slacken with time. There is a need, then, to monitor the system and to repeat the risk analysis at regular intervals.

A risk assessment needs to be tailored to the needs of the government, community, asset owner, regulator and other stake-holders and decision-makers. There are many tools and methods available for conducting a risk assessment (e.g., [49]). Analysis methods can be qualitative, quantitative or a combination of the two.

The International Organization for Standardization *Bases for Design of Structures—General Principles on Risk Assessment of Systems Involving Structures* [24] provides detailed and critical evidence-based advice on the utility of qualitative and quantitative risk analyses.

In quantitative estimation, numerical values (rather than descriptive scales used in qualitative estimation) are used for both consequences and probability of occurrence based on data and analyses from a variety of sources. Such an assessment is termed a Quantified Risk Analysis (QRA) or a Probabilistic Risk Analysis (PRA). A flowchart of the PRA process for structural systems is shown in Figure 1.6 [24].

A key feature of a PRA (or any other quantitative risk assessment) is that it provides robust and evidence-based advice on the actual level of risk, and this can be compared directly with acceptable risk criteria that are well established in society (e.g., [50]). The process of quantification is fully transparent, as are assumptions and

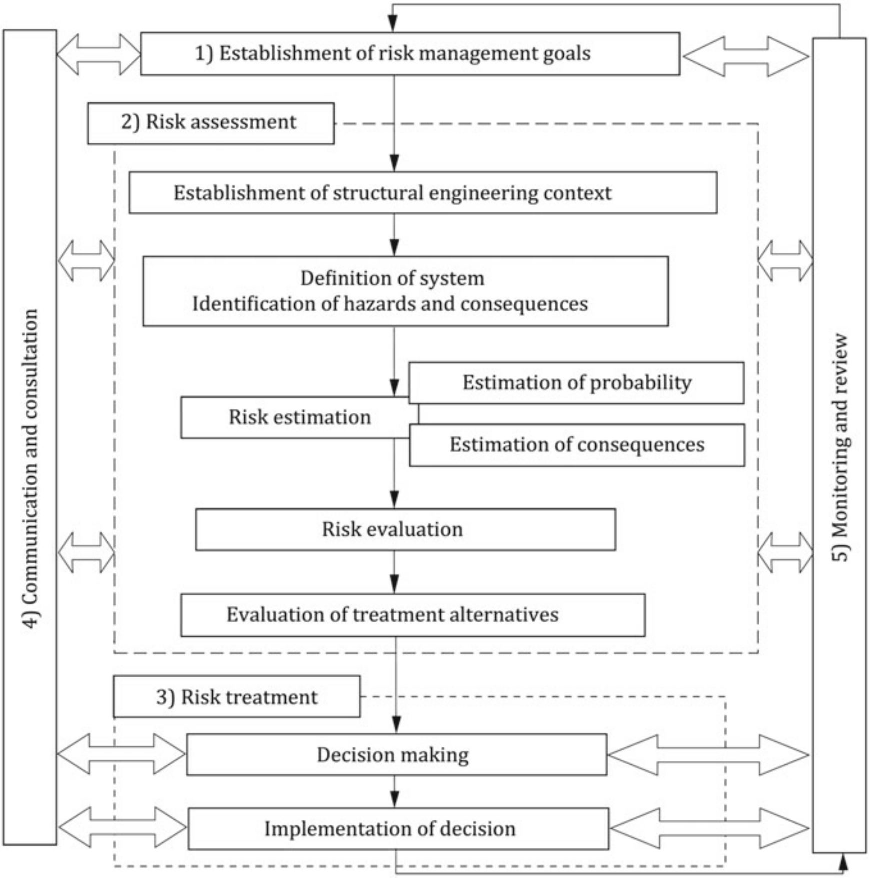

Fig. 1.6 Flowchart of probabilistic risk assessment. (adapted from [24])

data gaps during this process. Moreover, sensitivity analyses can be conducted to test the robustness of decisions—this is particularly important if there is uncertainty about hazard, vulnerability, exposure or consequences.

The risk shown in Eq. 1.1 can be re-expressed as:

$$\mathrm{E(L)} = \sum \mathrm{Pr(H)Pr(D|H)Pr(L|D)L} \tag{1.2}$$

where Pr(H) is the probability that a specific hazard will occur, Pr(D|H) is the probability of infrastructure damage or other undesired effect conditional on the hazard (also known as fragility) for the baseline case of no extra protection (i.e. 'business as usual'), Pr(L|D) is the conditional probability of a loss (economic loss, loss of life, etc.) given occurrence of the damage, and L is the loss or consequence if full damage occurs. The product Pr(D|H)Pr(L|D)L refers to the expected loss given the occurrence of the hazard. In some cases, 'damage' may equate to 'loss' and so a vulnerability function may be expressed as Pr(L|H) which is equal to the product Pr(D|H)Pr(L|D). The summation sign in Eq. 1.2 refers to the number of possible hazards, damage levels and losses. If the loss refers to a monetary loss, then E(L) represents an economic risk.

In many cases, the probability of occurrence of a threat, hazard, damage or consequence cannot be described adequately by single-point values (best estimates). An example is when there is a large amount of uncertainty about an event frequency. In this case, it is appropriate to retain the uncertainties associated with the event frequency by modelling event frequency as a probability distribution, and allow the risk analysis to propagate these uncertainties throughout the analysis. This may be termed a Probabilistic Risk Analysis (e.g., [49]) or more simply 'uncertainty modelling'. Uncertainty modelling can consider aleatory (random variation inherent in real life events) and epistemic (knowledge uncertainty inherent in the model of the world and associated scientific algorithms) uncertainties.

The expected loss after risk mitigation or other protective measure is derived from Eq. 1.2 as

$$\mathrm{E_{mitigation}} = \sum (1 - \Delta \mathrm{R})\mathrm{E(L)} - \Delta \mathrm{B} \tag{1.3}$$

where ΔR is the reduction in risk caused by risk mitigation or other protective measure, E(L) is the 'business as usual' risk given by Eq. 1.2, and ΔB is the co-benefit such as reduced losses to other hazards, increased energy efficiency of new materials, etc. Costs of protection, timing of these measures, discount rates, future growth in infrastructure and spatial and time-dependent changes in hazards need to be included in any risk analysis.

1.4.1 Hazard Assessment

There are significant challenges in characterizing (in probabilistic terms) the hazard in time and space. While significant advances have been made in doing just that, there remains considerable uncertainty in some aspects of hazard characterization and modelling. These uncertainties, of course, propagate through the risk analysis.

Hazard characterization often is in the purview of disciplinary scientists/experts rather than the engineer conducting the risk analysis. Even modern load standards for structural design (such as ASCE 7 in the US) are developed using critical information provided by, for example, seismologists, meteorologists, hydrologists, and other domain specialists. While this has the advantage of generally more sophisticated models, likely to be more accurate, such hazard models (particularly those that are physics-based) are often very computationally intensive and may be difficult to incorporate into generalized (e.g., regional) risk analysis or time-dependent risk analyses using numerical simulation. The adaptation, simplification, or generalization of these hazard models for such purposes is the responsibility of the engineer.

Hurricane hazard modelling in the last decade has expanded in sophistication to include both temporal and spatial characteristics using event-based simulation models. This has allowed, for example, the characterization of hurricane intensity and spatial extent (size) as a function of time and location [29, 61]. Such models have been successfully coupled with rainfall rate models [30] and, most recently, have been extended to include explicit consideration of projected climate change, specifically warming sea surface temperatures [62]. Nonetheless, uncertainties associated with future CO_2 emission scenarios are usually not quantified and future climate projections are produced separately for individual scenarios [55].

As engineers, we are often challenged with selection of appropriate scales, levels of detail, and granularity of both analysis and solution. This is especially true in hazard assessment and modelling where different hazards may be modelled/characterized at different scales, and in cases where hazard models may have vastly different confidence levels from one another and from the embedded mathematical models in the risk analysis framework.

The issues of concurrent or concomitant hazards must also be included in some risk analyses. Examples include hurricane (wind) and coastal flooding, seismic and urban fire, wind and wildfire.

Finally, most risk analyses account only for the hazards we know to exist presently. Failure to consider emerging hazards, and those we may not be able to envision today, may in fact contribute the greatest uncertainty to any risk analysis. Consider, for example, the events of 9/11. No structure had been designed for the direct impact of a fully fuel-loaded passenger jet. It was not even in the realm of possibility. Elms [5] refers to this as ontological uncertainty—a third type of uncertainty after aleatoric and epistemic.

1.4.2 Fragility and Vulnerability

Infrastructure fragility or vulnerability can be expressed in terms of structural damage or other losses, and are derived from fitting curves to damage data from historical damage records (i.e. empirical models and insurance data) or from engineering models (e.g., [49]).

Insurance or building performance data are often used to derive vulnerability models which are often expressed in terms of Pr(L|H). For example, Fig. 1.7 shows a vulnerability model for Australian houses subject to floods derived from insurance loss records. In this case, the hazard H is the water depth above the floor. Empirical models have draw-backs such as, lack of damage data [16], lack of capability to examine the effect of changes in building design and construction methods on damages, lack of ability to examine the effectiveness of building adaptation measures for climate change [67], and they tend to focus on losses (vulnerability) and not damage (fragility). There are also a number of issues associated with utilising claim data such as access to the insurance claim data, insurance valuation cost and the actual damage cost, and insurance claim databases that do not disaggregate losses between building exterior and interior [41]. Most importantly, empirical vulnerability curves are based on what has happened in the past. They cannot assess changes in fragility or vulnerability due to future changes in design standards, materials or construction practices. This highlights the need of developing fragility models based on engineering and structural reliability methods. It is noted however that, as with all models, engineering fragility models should be validated or benchmarked with empirical models based on past events where possible to give more confidence in modelling assumptions and realism.

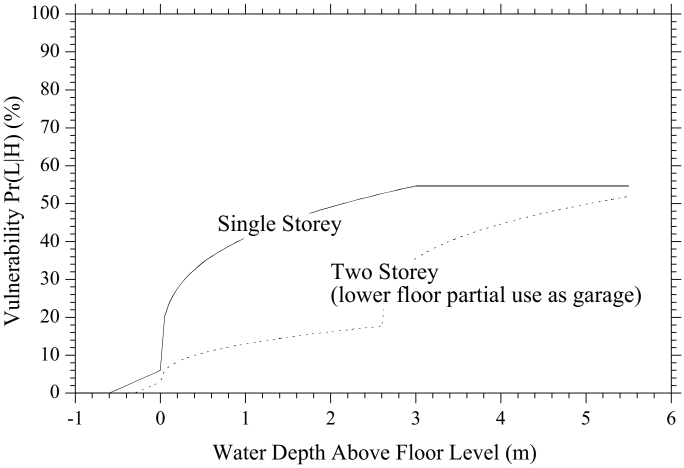

Fig. 1.7 Flood vulnerability curves for residential construction in Brisbane (data from [28])

The stochastic modelling of infrastructure fragility is Pr(D|H) and is the probability of damage conditional on a specific wind speed, flood level, earthquake or other hazard:

$$\Pr(D|H) = \Pr(R(\mathbf{X}) - H < 0) \tag{1.4}$$

where R(**X**) is the function for resistance or capacity, **X** is the vector of all relevant variables that affect resistance, and H is the known hazard level. Fragility modelling will require probabilistic information on materials, dimensions, model errors, deterioration and other input variables (**X**) into engineering models which define the resistance function R(**X**)—these variables vary in time and space.

A key challenge, at least for engineers, is the development of fragility models for damage prediction. Most damage and loss from floods and storms are not due to major structural failure or collapse, but due to water ingress from damaged roofs or walls, or rising water levels. There is much work on predicting reliabilities for the ultimate limit state (collapse) where life-safety is the major criterion. However, modelling of damage and serviceability limit states is a less tractable problem as this requires advanced simulation modelling to accurately track component and member performance and failure, load sharing, failure of other components/members due to load redistribution, and damage progression leading to economic and other losses.

Another challenge is that infrastructure, particularly houses, are very complex systems comprising of hundreds to thousands of components and members (some engineered, and some not) of differing materials. Poor detailing and workmanship issues contribute to most damage—so the engineering and stochastic models need to consider these variables—such as screw fasteners being spaced too far apart, or some not connected to purlins and battens, etc. (e.g., [43]). These are more challenging to model stochastically than more conventional 'engineered' constructions such as bridges, towers, etc. where materials are more uniform, and workmanship subject to more quality control measures. Stewart et al. [54] have conducted structural reliability analyses to assess the roof envelope fragility Pr(D|H) of contemporary timber-framed houses built in the Australian city of Brisbane, see Fig. 1.8. In this case, Monte-Carlo simulation and structural reliability methods were used to stochastically model spatially varying pressure coefficients, roof component failure for 1600 roof fasteners and 500 battens, load re-distribution and spatial variability across the roof as connections progressively fail, loss of roof sheeting as a critical number of connections fail, and changes in internal pressure coefficient with increasing roof sheeting loss. The fragility of the roof envelope vulnerable to dominant openings on the windward wall, and also to construction defects.

1.4.3 Losses

Exposure and loss data relates to direct and indirect loss or consequence due to location and extent of infrastructure damage, for existing exposure and future projections.

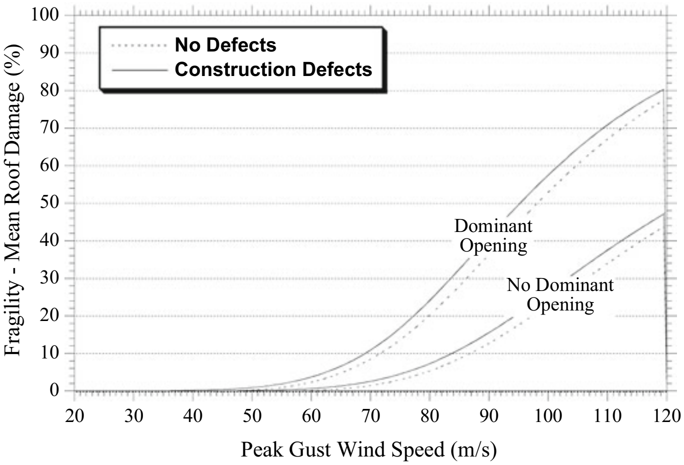

Fig. 1.8 Fragility curves for Australian timber-framed housing (adapted from [54])

A probability of loss Pr(L|D) and loss L needs to consider direct and indirect losses, however, most existing studies consider direct losses related to infrastructure damage and contents losses. For example, Fig. 1.9 shows a typical direct loss function for wind vulnerability [19], for roofing and building interior losses. It is observed that the trend between extent of damage (D) and loss is non linear, and that losses reach close to their maximum value when damage is only 20%. Clearly, losses accumulate rapidly for low levels of damage because “once the envelope is breached, most of the damage to the interior of the building is a function of the amount of water that enters the building” [19].

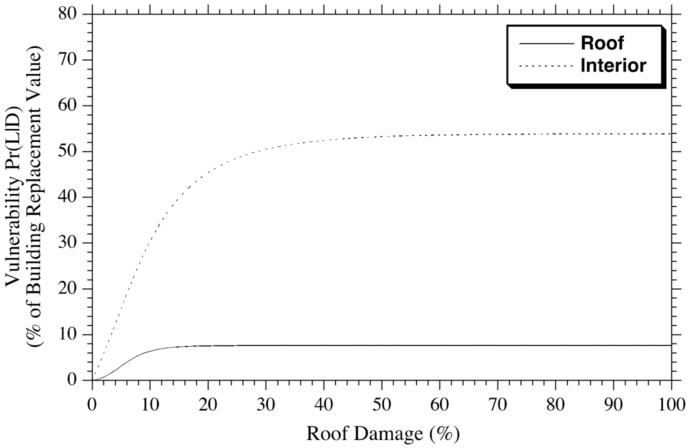

Fig. 1.9 Components of building loss due to wind

Indirect losses caused by business interruption, clean-up, loss during reconstruction, extra demands on social services, and changes to demand and supply of intermediate consumption goods, post-disaster inflation, etc. can also be significant (e.g. [14, 34, 60]). The data is very limited to accurately quantify how indirect losses increase with vulnerability. Indirect losses were estimated for Hurricane Katrina using an adaptive regional Input–Output model where damage to houses was $20 billion, contents $7 billion, $17 billion damage to government, and $63.5 billion to the private sector—total damage to fixed capital was $107 billion [14]. The total indirect loss is $42 billion or 39% of direct losses. Hallegatte [14] estimates that indirect losses could exceed 100% of direct losses for a damaging event twice as bad as Hurricane Katrina. An Australian assessment of direct and indirect costs shows indirect costs of 9–40% of direct losses for bushfire, cyclones and floods [2].

There is often a high level of post-disaster inflation (or demand surge) of reconstruction costs (e.g., [60]) which can lead to higher insurance and home owner losses. Walker [60] estimates that the post-disaster inflation was close to 100% for Cyclone Tracy.

Finally, resiliency is a term that is increasingly being applied to disaster risk reduction. It may be defined as the ability of the system to restore functionality after a damaging event, and the time needed to achieve full restoration of the system is affected by social, economic, and political aspects (e.g. [7, 47]). Or it may be defined more broadly to capture vulnerability, exposure or loss. Resiliency in one way or another has been included in most risk assessments, particularly for low probability—high consequence events, when assessing loss likelihoods and magnitudes. For example, an urban community that has ready access to emergency services that can temporarily place tarpaulins over damaged roofs will reduce water ingress losses and allow inhabitants to remain in their homes—the community will be able to recover more quickly from such a disaster, and so direct and indirect losses will be minimised. This 'bouncing back' implies a return to the status quo, whereas, 'bouncing forward' leads to continually improving conditions which is a more desired outcome [21]. While the term 'resiliency' may not appear explicitly in risk modelling, it is implied in many cases.

1.4.4 Risk Reduction

A risk treatment or mitigation measure should result in risk reduction (ΔR) that may arise from a combination of reduced fragility or vulnerability (Pr(D|H) or Pr(L|D)) or exposure (L). For instance, changes to planning may reduce the number of new properties built in a flood plain which will reduce L, or more stringent design codes may reduce the fragility of new infrastructure. Systems and reliability modelling are essential tools to quantify the level of risk reduction, and the extent of risk reduction will depend on the hazard, location, and timing of protective measure. For any risk mitigation or protective measure the risk reduction ΔR can vary from 0 to 100% (or even a negative number for an ill-suited measure).