



Institute for Catastrophic  
Loss Reduction  
Building resilient communities

Institut de prévention  
des sinistres catastrophiques  
Bâtir des communautés résilientes

ICLR's  
**HailSmart**<sup>™</sup>  
PROGRAM

## A benefit-cost analysis of impact-resistant asphalt shingle roofing

By Keith Porter, PE, PhD, ICLR Chief Engineer

March 2022





# **A benefit-cost analysis of impact-resistant asphalt shingle roofing**

Authored by:

Keith Porter, PE, PhD, ICLR Chief Engineer

March 2022

ICLR research paper series – number 72

*Published by*

Institute for Catastrophic Loss Reduction

20 Richmond Street East, Suite 210

Toronto, Ontario, Canada M5C 2R9

This material may be copied for purposes related to the document as long as the authors and copyright holders are recognized.

The opinions expressed in this paper are those of the author and not necessarily those of the Institute for Catastrophic Loss Reduction.

Front cover: (left) Roofer working on a home in Oklahoma (FEMA photo library); (right) Hail being measured (IBHS). Back cover: (left) Four test tubes (ICLR); (right) Handful of hail (IBHS). Prepared for Institute for Catastrophic Loss Reduction, Toronto, 66 pp.

ISBN: 978-1-927929-37-7

Copyright © 2022 Institute for Catastrophic Loss Reduction

Established in 1997 by Canada's property and casualty insurers, the **Institute for Catastrophic Loss Reduction** is an independent, not-for-profit research institute based in Toronto and at Western University in London, Canada. The Institute is a founding member of the Global Alliance of Disaster Research Institutes. The Institute's research staff are internationally recognized for pioneering work in a number of fields including wind and seismic engineering, atmospheric sciences, water resources engineering and economics. Multi-disciplined research is a foundation for the Institute's work to build communities more resilient to disasters.



ICLR has been designated as an IRDR International Centre of Excellence. IRDR International Centres of Excellence (ICoEs), established through the IRDR Scientific Committee (SC) and the relevant National

Committee (NC), provide regional and research foci for the IRDR program. ICoE research programs embody an integrated approach to disaster risk reduction that directly contribute to the ICSU/IRDR Science Plan for Integrated Research on Disaster Risk and its objectives, as well as the IRDR Strategic Plan (2013-2017).

## **Acknowledgements**

The author thanks Anne Cope, Kim Court, Stephen Decoteau, Marla Desat, Vincent Faucher, Wendy Fraser, Paul Joe, James Klassen, Paul Kovacs, Véronic Lavigne, Bohan Li, Gordon McBean, Vincent Roy, Dan Sandink, and Kevin Wallis, who provided valuable insight into hail meteorology and mitigation. Bohan Li, Glenn McGillivray and Dan Sandink also helped with proofreading and checking calculations.

### **Recommended citation**

Porter, K.A. (2022). *A Benefit-Cost Analysis of Impact-Resistant Asphalt Shingle Roofing*. Institute for Catastrophic Loss Reduction, Toronto, ON, 66 p.

## Executive summary

The Institute for Catastrophic Loss Reduction creates and disseminates disaster resilience knowledge for Canada. Among the catastrophes ICLR addresses are hailstorms, one of Canada's most serious natural hazards. Hail costs \$400 million annually. A June 2020 hailstorm at the edge of Calgary damaged 77,000 homes and cost \$1.4 billion. Much of that money paid for roof repairs. A direct hit on Calgary could be 5 to 10 times worse. Though the hailstorm is inevitable, the catastrophe is not. This document summarizes a study of one way that homeowners and insurers can prevent costly hail damage: by using impact-resistant asphalt shingle roofs instead of standard shingles.

Impact-resistant roof shingles look like ordinary shingles, but have material that makes them resistant to hail damage. When struck by large hailstones, they resist pits and fractures that would otherwise allow water to pool or penetrate beneath them. And they resist cosmetic damage like the loss of granules: the specks that cover the shingle surface.

**The Institute for Catastrophic Loss Reduction performed a benefit-cost analysis of impact-resistant asphalt roof shingles. The analysis shows that the shingles save more than they cost in Hailstorm Alley and many other places.**



**Impact-resistant**



**Non-impact-resistant**

**Hail resilience has costs and benefits**

**For a 170-m<sup>2</sup> (1,800-ft<sup>2</sup>) impact-resistant roof in Calgary:**

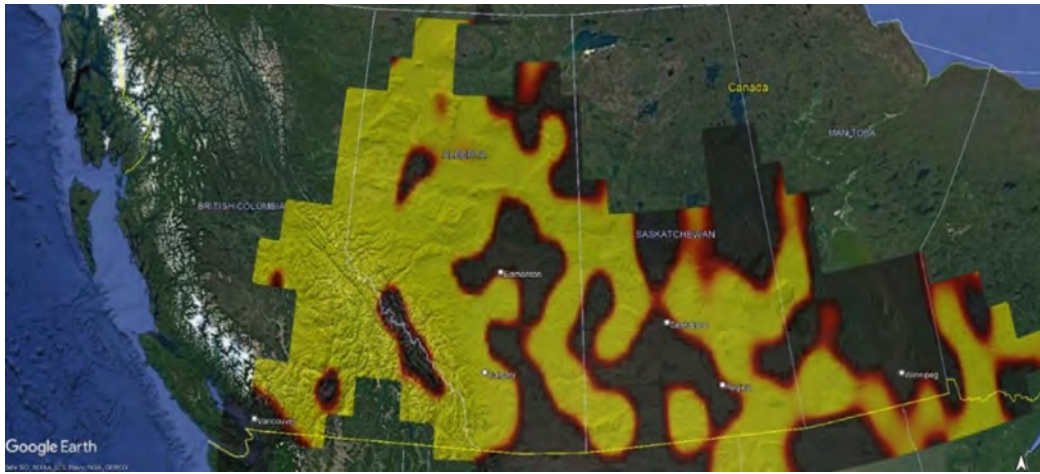
**Cost = \$3,400**

**Benefit = \$10,000**

**Benefit-cost ratio = 3:1**

**Benefit-cost ratio reaches 8:1 elsewhere**

Impact-resistant shingles can add 50% to the cost of a roof. For a 170-m<sup>2</sup> (1,800-ft<sup>2</sup>) roof, the added cost is \$3,400. This study used a method called performance-based engineering to estimate how much loss the shingles prevent, compared with standard shingles. One can compare the costs and benefits on an apples-to-apples basis.



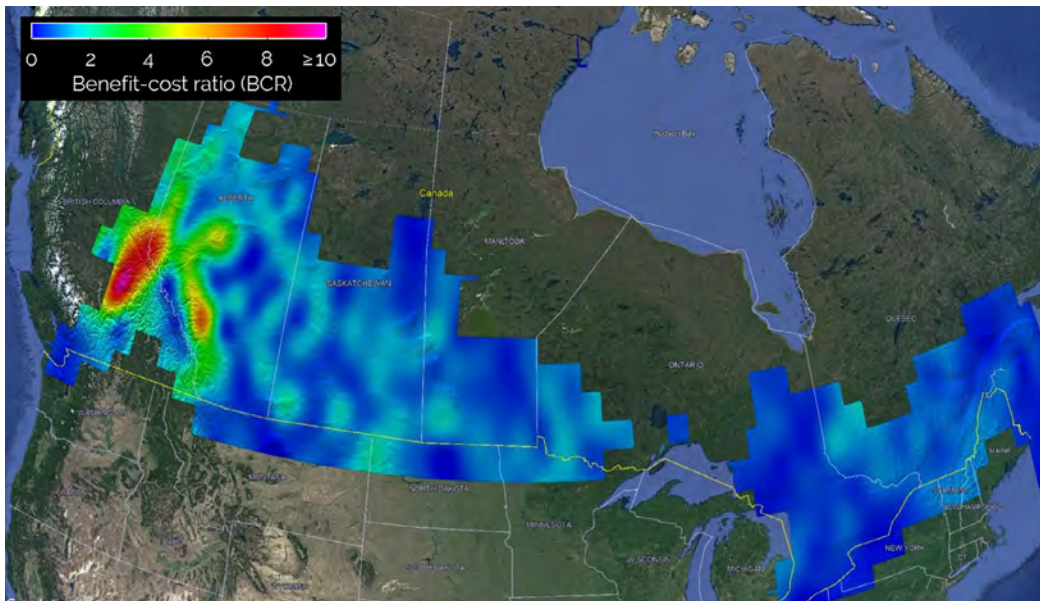
**Figure ES-1.** Yellow shows where impact-resistant shingles more than pay for themselves on average.

### Impact resistant shingles make financial sense across all of Hailstorm Alley

The shingles are cost effective wherever it hails almost once a year or more, the yellow areas in Figure ES-1. Climate change will worsen future hailstorms, making impact-resistant shingles more valuable and the yellow area bigger.

### Impact resistant shingles can save 8 times what they cost

In Calgary, impact-resistant shingles reduce the chance of damage by 15 times. If the roof is damaged, average repair cost drops by half. Considering how frequently hailstorms happen, that saves \$3 for every \$1 in added cost, or \$10,000 over a life of a roof. The shingles pay for themselves in 5 years, on average. (That assumes one repairs the roof every time it gets damaged.) Figure ES-2 shows where the shingles are most cost effective: red means savings 8 times the cost.



**Figure ES-2.** Benefit-cost ratio (BCR) for class-4 (the highest on a 1-to-4 rating scale) impact-resistant asphalt shingles. The shingles more than pay for themselves anywhere colored light blue or warmer, wherever the benefit is more than 1 times the cost.

The costs and benefits scale up or down with roof size. Equations in the technical report show a mathematically-inclined reader how to scale the costs and benefits for different sized roof and different locations. Like all studies, this one has its assumptions, limitations, technical details, and suggestions for future research. See chapter 5 to learn more.



**What does an impact-resistant shingle resist?**

A 55-g, 50-mm hailstone falling at terminal velocity from 1 km strikes like a 550-g, 50-mm steel ball falling 6 metres. That is like the worst impact by the biggest hailstone in 99% of storms.



1,000 m    6 m

# Table of contents

|   |      |
|---|------|
| <b>Acknowledgements</b> .....   | i    |
| <b>Executive summary</b> .....  | ii   |
| <b>List of figures</b> .....  | vii  |
| <b>List of tables</b> .....   | viii |
| <b>Abbreviations and notations</b> .....                                      | ix   |
| <b>1. Introduction</b> .....  | 1    |
| 1.1 Motivation and audience .....   | 1    |
| 1.2 Objectives and scope .....  | 1    |
| 1.3 Organization of the report .....  | 2    |
| <b>2. Literature review</b> .....   | 3    |
| 2.1 Performance-based engineering .....                                       | 3    |
| 2.2 Prior hail benefit-cost analyses and risk studies .....                   | 3    |
| 2.3 Roofing .....   | 4    |
| 2.3.1 Roofing systems .....   | 4    |
| 2.3.2 Asphalt shingles .....  | 5    |
| 2.3.3 Shingle impact rating .....   | 6    |
| 2.3.4 Some common lines of impact-resistant shingles .....                    | 7    |
| 2.4 Hazard .....  | 8    |
| 2.4.1 Hail formation, physical properties, and terminal velocity .....        | 8    |
| 2.4.2 Hailstorm frequency .....   | 9    |
| 2.4.3 Hailstorm hitrate and duration (volume or count per square meter) ..... | 10   |
| 2.4.4 Hailstone size distribution .....                                       | 11   |
| 2.4.5 Climate change .....  | 11   |
| 2.4.6 Hail seeding .....  | 12   |
| 2.5 Fragility functions and derivation methods .....                          | 12   |
| 2.6 Damage and loss .....   | 13   |
| 2.6.1 Hail impact physics .....   | 13   |
| 2.6.2 Damage symptoms .....   | 13   |
| 2.6.3 Asphalt shingle hail fragility .....                                    | 14   |
| 2.6.4 Asphalt shingle repair cost .....                                       | 15   |
| 2.6.5 Depreciation .....  | 16   |
| 2.6.6 Incentives to promote mitigation .....                                  | 16   |
| <b>3. Proposed methods</b> .....  | 17   |
| 3.1 Performance-based engineering .....                                       | 17   |
| 3.2 Asset definition .....  | 19   |
| 3.3 Hazard analysis .....   | 19   |



|           |   |           |
|-----------|---|-----------|
| 3.4       | Damage analysis . . . . .   | 23        |
| 3.4.1     | Limit states of interest . . . . .  | 23        |
| 3.4.2     | Fragility of non-impact-resistant shingles . . . . .                                    | 23        |
| 3.4.3     | Fragility of impact-resistant shingles . . . . .  | 25        |
| 3.4.4     | Have we ignored important fragility data? . . . . .                                     | 27        |
| 3.4.5     | Simplifying the damage analysis with DL as the demand parameter . . . . .               | 27        |
| 3.5       | Loss analysis . . . . .   | 29        |
| 3.5.1     | Repair cost as a function of damage . . . . .   | 29        |
| 3.5.2     | Long-term average annualized loss . . . . .   | 30        |
| 3.5.3     | Frequency-severity formulation of loss . . . . .  | 31        |
| 3.6       | Benefit-cost analysis . . . . .   | 31        |
| 3.6.1     | Benefit-cost ratio . . . . .  | 31        |
| 3.6.2     | Insurer's decision situations . . . . .   | 32        |
| 3.6.3     | Buyers who do not expect to recoup the higher price of the roof . . . . .               | 33        |
| 3.6.4     | Societal viewpoint . . . . .  | 34        |
| <b>4.</b> | <b>Findings . . . . .</b>   | <b>35</b> |
| 4.1       | Sample building and locations . . . . .   | 35        |
| 4.2       | Marginal cost and replacement cost . . . . .  | 35        |
| 4.3       | Hazard and fragility . . . . .  | 36        |
| 4.4       | Loss analysis . . . . .   | 36        |
| 4.5       | Frequency, severity, benefit, cost, and benefit-cost ratio . . . . .                    | 37        |
| 4.5.1     | Results . . . . .   | 37        |
| 4.5.2     | Observations and interpretation of results . . . . .                                    | 38        |
| 4.5.3     | Sensitivity tests . . . . .   | 40        |
| 4.5.4     | Sensitivity to the fragility function . . . . .   | 40        |
| 4.5.5     | Effect of geographic location on frequency and benefit-cost ratio . . . . .             | 42        |
| 4.6       | Climate change . . . . .  | 44        |
| <b>5.</b> | <b>Conclusions . . . . .</b>  | <b>45</b> |
| 5.1       | Successful creation of a performance-based engineering method for hail damage . . . . . | 45        |
| 5.2       | The business case for an insurer to rebuild stronger homes . . . . .                    | 45        |
| 5.3       | The societal business case for impact-resistant roofs . . . . .                         | 45        |
| 5.4       | The results scale . . . . .   | 46        |
| 5.5       | Study limitations . . . . .   | 46        |
| 5.6       | Future research . . . . .   | 47        |
| <b>6.</b> | <b>References cited . . . . .</b>   | <b>49</b> |

## List of figures

|                   |   |    |
|-------------------|---|----|
| <b>Figure 1.</b>  | Parts of an asphalt shingle roof. . . . .   | 4  |
| <b>Figure 2.</b>  | Asphalt shingle cross section . . . . .   | 5  |
| <b>Figure 3.</b>  | Average annual number of days with hail (ICLR 2018) . . . . .   | 9  |
| <b>Figure 4.</b>  | (A) Number of observations exceeding minimum equivalent diameter of largest hailstone, (B) average (blue) and smallest (red) diameter, (C) duration, and (D) hitrate as functions of equivalent diameter of largest hailstone. The upper x-axis shows maximum diameter of the largest hailstone in mm (Grieser and Hill 2019) . . . . . | 10 |
| <b>Figure 5.</b>  | (A) A hail-damaged roof, showing discoloration because of the loss of granules. (B) Illustration of hail damage. Source: Roofingcalc.com (2021), usage claimed under fair use doctrine . . . . .  | 14 |
| <b>Figure 6.</b>  | Second-generation performance-based earthquake engineering framework . . . . .  | 18 |
| <b>Figure 7.</b>  | Hailstorm frequency in 2021, denoted by $f_h(2021)$ , taken from Etkin (2018) . . . . .   | 19 |
| <b>Figure 8.</b>  | Cumulative distribution function of equivalent diameter of largest hailstone $D_L$ implied by Grieser and Hill (2019) . . . . .   | 20 |
| <b>Figure 9.</b>  | Cumulative distribution function of hailstone diameter with average = 18 mm and $\alpha = 1.75$ . . . . .   | 21 |
| <b>Figure 10.</b> | Fragility of non-impact-resistant laminated shingles as implied by Marshall et al. (2002) tests . . . . .   | 24 |
| <b>Figure 11.</b> | Fragility of asphalt shingles to the strike of a single hailstone . . . . .   | 26 |
| <b>Figure 12.</b> | Shingle failure probability as a function of the storm's largest hailstone. . . . .   | 28 |
| <b>Figure 13.</b> | Canada inflation rate (Trading Eco 2021) . . . . .  | 32 |
| <b>Figure 14.</b> | How planning period and discount rate affect benefit and benefit-cost ratio . . . . .   | 39 |
| <b>Figure 15.</b> | Societal benefit-cost ratio for impact-resistant shingles in Hailstorm Alley, and its sensitivity to various inputs. The vertical dotted line at $x = 1:1$ indicates breakeven: left is $BCR < 1:1$ , right is $BCR > 1:1$ . . . . .  | 40 |
| <b>Figure 16.</b> | Benefit-cost ratio for class-4 impact-resistant asphalt shingles near Hailstorm Alley. . . . .  | 42 |
| <b>Figure 17.</b> | Benefit-cost ratio for class-4 impact-resistant asphalt shingles across much of the nation. . . . .   | 42 |
| <b>Figure 18.</b> | Insurer claim frequency for unrated asphalt shingles near Hailstorm Alley. . . . .  | 43 |
| <b>Figure 19.</b> | Insurer claim frequency for class-4 impact-resistant asphalt shingles near Hailstorm Alley. . . . .   | 43 |

## List of tables

|   |    |
|---|----|
| <b>Table 1.</b> Some common lines of impact-resistant shingles . . . . .  | 8  |
| <b>Table 2.</b> Marshall et al. (2002) ice-ball impact tests of various roofing products . . . . .                      | 14 |
| <b>Table 3.</b> Shingle fragility for breaching moisture barrier . . . . .  | 25 |
| <b>Table 4.</b> Shingle fragility in terms of the equivalent diameter of the storm's largest hailstone, $D_L$ . . . . . | 29 |
| <b>Table 5.</b> Expected fraction of roof value lost given a hailstorm, by hail rating, $F_L$ . . . . .                 | 31 |
| <b>Table 6.</b> Sample building and locations . . . . .   | 35 |
| <b>Table 7.</b> Contributors to repair cost per roofing square . . . . .  | 36 |
| <b>Table 8.</b> Benefit-cost ratio of using impact-resistant asphalt shingle roofing near Calgary, Alberta . . . . .    | 38 |

## Abbreviations and notation

|                       |   |                        |  |
|-----------------------|---|------------------------|--|
| $\alpha$              | Shape parameter   | <b>H</b>               | Intensity measure  |
| $\beta$               | Inverse scale parameter, or logarithmic standard deviation                              | <b>hr</b>              | Hours  |
| $\Gamma$              | Gamma distribution  | <b>Hr</b>              | Hirate   |
| $\theta$              | Median  | <b>HST</b>             | Harmonized sales tax   |
| $\Phi$                | Standard normal cumulative distribution function  | <b>in</b>              | Inches   |
| $\Pi$                 | Product   | <b>kg</b>              | Kilograms  |
| $\tau$                | Planning period   | <b>km</b>              | Kilometres   |
| <b>a</b>              | A parameter   | <b>k<sub>n</sub></b>   | Spring stiffness   |
| <b>A</b>              | Area  | <b>kN</b>              | Kilonewtons  |
| <b>ANSI</b>           | American National Standards Institute   | <b>L</b>               | Loss measure   |
| <b>b</b>              | Y-intercept of a line or a parameter  | <b>lb</b>              | Pounds   |
| <b>B</b>              | Benefit   | <b>ln</b>              | Natural logarithm  |
| <b>BCR</b>            | Benefit-cost ratio  | <b>m</b>               | Metres, or slope of a line   |
| <b>C</b>              | Degrees centigrade or repair cost   | <b>min</b>             | Minutes  |
| <b>CAD</b>            | Canadian dollars  | <b>mm</b>              | Millimetres  |
| <b>COR</b>            | Coefficient of restitution  | <b>N</b>               | Number of hailstones   |
| <b>d</b>              | penny (nail size)   | <b>N/A</b>             | Not applicable   |
| <b>D</b>              | Number of damaged shingles per roofing square, or damage measure, or hailstone diameter | <b>nObs</b>            | Number of observations   |
| <b>D<sub>A</sub></b>  | Equivalent diameter of the average hailstone  | <b>OSB</b>             | Oriented strandboard   |
| <b>D<sub>L</sub></b>  | Equivalent diameter of the largest hailstone, a random variable                         | <b>p</b>               | Probability, a particular value  |
| <b>d<sub>L</sub></b>  | A particular value of DL  | <b>P[A B]</b>          | Probability of A given B   |
| <b>E</b>              | Threshold level of loss causing total loss  | <b>PV</b>              | Present value (of future loss)   |
| <b>EAL</b>            | Expected annualized loss  | <b>r</b>               | Discount rate  |
| <b>exp</b>            | Exponential function  | <b>R</b>               | Factor to account for repair difficulty, or structural response, or hailstone area density |
| <b>f<sub>ab</sub></b> | Fraction of hailstones between diameters a and b  | <b>RCP</b>             | Representative concentration pathway   |
| <b>f<sub>DL</sub></b> | Probability density function of DL  | <b>r<sub>max</sub></b> | Maximum excitation to which specimens are subjected  |
| <b>F<sub>D</sub></b>  | Cumulative distribution function of D   | <b>sec</b>             | Seconds  |
| <b>F<sub>DL</sub></b> | Cumulative distribution function of DL  | <b>sq</b>              | Roofing square (9.29 m <sup>2</sup> , 100 ft <sup>2</sup> )                                |
| <b>f<sub>h</sub></b>  | Frequency of hailstorms   | <b>t</b>               | Period of time   |
| <b>f<sub>0</sub></b>  | A small fraction of roof damage   | <b>T</b>               | Duration of hailstorm  |
| <b>FM</b>             | Factory Mutual  | <b>UL</b>              | Underwriters Laboratory  |
| <b>ft.</b>            | Feet  | <b>USD</b>             | United States dollars  |
| <b>G</b>              | Mean exceedance frequency   | <b>V</b>               | Value exposed to loss, or replacement cost new   |
| <b>GST</b>            | Goods and services tax  | <b>v<sub>0</sub></b>   | Hailstone velocity   |
|                       |   | <b>x</b>               | X-coordinate of a line   |
|                       |   | <b>y</b>               | Year, e.g., 2021   |
|                       |   | <b>yr</b>              | Years  |

# 1. Introduction

## 1.1 Motivation and audience

Severe hailstorms have the potential to produce economic catastrophes. In the average year since 2013, Canadian insurers have paid 26,000 claims totaling \$370 million in insured loss for personal property damage in hailstorms. The June 13, 2020, Calgary hailstorm resulted in 70,000 insurance claims and cost \$1.3 billion in insured losses, the fourth costliest natural disaster in Canadian history. An AIR study estimated that a direct-hit Calgary hailstorm could produce insured loss over \$10 billion (Robinson 2016). Such a hailstorm may be inevitable, but the economic catastrophe is not. People can change buildings before the storm to reduce the damage and loss. Anecdotal evidence from hailstorms and laboratory experiments (discussed later) suggest that the largest contributor to hail damage and loss to buildings comes from roof repair. The present study offers the business case for installing impact-resistant asphalt shingle roofing on buildings that would otherwise have non-impact-rated asphalt shingle roofs.

The study should interest several audiences. Hail damage matters to insurers because in an average year, an estimated 30-40% of shingles are, in a sense, purchased by insurers as part of an insurance claim (A. Cope, Insurance Institute for Business and Home Safety, verbal commun., November 22, 2021). Builders may want to understand the business case for building beyond code minima. Code-writing bodies might want to understand where and why to impose requirements for impact-resistant roofing. Governments might want to offer incentives for building owners to mitigate hail damage. Structural engineers may find value in the new performance-based hail engineering methodology developed here.

Few members of these audiences will get much value from this technical report. Most will prefer the executive summary to this report and other brief summaries that this report informs. But a few readers will need to examine the underlying analytical method, supporting data, input and outputs, and assumptions, and the briefer materials rely on the details presented here.

## 1.2 Objectives and scope

Asphalt roof shingle manufacturers have enhanced the impact resistance of some shingle products for example by adding a rubber-like polymer to the asphalt. The present work develops part of the business case for impact-resistant roofing. It first develops a general performance-based engineering methodology to evaluate the performance of impact-resistant roofing in terms of probabilistic repair costs. It then addresses these questions:

1. How can one estimate the costs and benefits of using impact-resistant asphalt shingle roofing for a new roof on a sample facility, using a performance-based approach?
2. What does the methodology imply about the cost-effectiveness of impact-resistant roof shingles on a typical single-family dwelling in Hailstorm Alley?
3. Should an insurer who covers a hail-damaged non-impact-resistant roof pay to rebuild the roof stronger, with impact-resistant shingles? Note that ICLR (2021) champions hail damage-reduction efforts following the 2020 Calgary hailstorm, including launch of ICLR's HailSmart™. The present study contributes to ICLR's efforts to strengthen hail research, partly to inform its *Insurers Rebuild Stronger Homes* program.

4. Does it make financial sense for an uninsured homeowner to pay more for an impact-resistant roof? ICLR (2018) advocates for homeowners to install class-4 impact-resistant roofing for all homes located in regions of moderate or high risk of hail. (Class 4 refers to a 0-to-4 rating system where 4 reflects the greatest resistance to hail. More details later.) The present study is partly intended to map the geographic locations where impact-resistant roofing makes the most financial sense under current climate conditions and for the next few decades.

This study only applies the method to laminated asphalt shingle roofing. It only superficially addresses 3-tab shingles and premium shingles. It does not address changing asphalt shingle roofing to different materials such as metal. Nor does it examine siding, vehicles, agriculture, or hail seeding. The performance-based method developed here can be applied to those issues at another time. The study does not attempt to estimate costs and benefits for buildings in other countries, although again its methods can be readily applied elsewhere.

### **1.3 Organization of the report**

This chapter presents motivation and scope of the study. Chapter 2 reviews much of the relevant literature. See chapter 3 for a proposed performance-based engineering method to estimate the costs and benefits of impact-resistant roofing. Chapter 4 presents findings after applying the method to a particular hypothetical house. See chapter 5 for general conclusions. Chapter 6 presents a listing of references cited.

## 2. Literature review

A benefit-cost analysis of impact-resistant roofing for hail damage requires a review of the leading methods to estimate benefits and costs, as well as important references on roofing, hail hazard, hail damage, and repair costs. These are now presented.

### 2.1 Performance-based engineering

Performance-based engineering is a framework that engineers use to estimate the future performance of buildings and other assets in terms that owners, tenants, and others care about most, namely repair costs, life-safety impacts, and loss of function (“dollars, deaths, and downtime”). As developed since about 2000 (e.g., Porter 2003), performance-based engineering offers some additional unique capabilities that are particularly important here. One can estimate how a small but potentially important design choice such as the impact-resistance rating of the roof affects future repair costs. One can quantify and propagate all important sources of uncertainty through the analysis to calculate expected values of loss and loss with various degrees of likelihood. One need not possess large quantities of actuarial-quality data that directly relate all features of the asset’s design and its past performance.

### 2.2 Prior hail benefit-cost analyses and risk studies

Several authors have examined the engineering economics of various aspects of hail risk. Robinson (2016) reports on an AIR study that estimated that a direct-hit Calgary hailstorm could produce insured loss over \$10 billion, if maximum hailstone size reached 100 mm. Pang (1999) recaps a study by Manitoba Public Insurance into the cost-effectiveness of gluing, versus welding, automobile roof panels to facilitate hail repairs: doing so saves \$400 per car roof.

Several authors estimated the economics of hail suppression. Sonka and Chagnon (1977) outline a method to estimate the benefits of hail suppression in terms of reduced crop losses. They estimate a modest benefit-cost ratio (1.2:1) for Kansas. Borland (1977) offers an interesting index of hail damage potential to residential buildings, in units of mean damage factor per year. Swanson et al. (1978) and Chagnon et al. (1978) estimate that hailstorm seeding could produce high benefit-cost ratios (perhaps 15:1) by reducing future US crop losses.

None of these works offers a benefit-cost analysis of impact-resistant asphalt shingles, siding, glazing, or other elements of the building envelope. Notably, the Insurance Institute for Business and Home Safety (2013) subjected a full-scale building to a realistic hailstorm in its test chamber, finding (among many other things) that “The majority of hailstone impacts were on the roofing system; this is very typical of what IBHS researchers have seen when conducting post-hailstorm damage investigations in the field and in numerous claims studies.” This finding supports the choice of roofing for an initial benefit-cost analysis of methods to improve the hail resilience of buildings.

## 2.3 Roofing

Most Canadian roofs are covered with asphalt shingles. A statistical sample by ICLR (Porter et al. 2021) found that approximately 85% of single-family dwellings in Canada's wildland-urban interface use this kind of roof covering. Approximately 14% have metal roof covers. The remainder have wood shingles or other materials.

Interestingly, Canada and the United States are unusual in their preference for asphalt shingles. Mexico mostly relies on roof membrane sheets applied by torch to concrete roof decks, both for residential and commercial construction (Gonzales 2007). Japan mostly uses ceramic tiles, at a cost of about \$20,000 CAD to replace a roof on a typical house. UK homes mostly use slate, clay, or concrete tiles, at a cost of about \$10,000 CAD for a new roof (Roof Advisor 2021). Replacing an asphalt shingle roof on a 200m<sup>2</sup> roof costs about \$5,000 CAD, as will be shown later.

Absent prior studies on the efficacy of greater hail impact resistance for asphalt shingle roof coverings, let us first summarize the construction of roofs, describe asphalt shingles, and review hail-impact rating systems for asphalt shingles.

### 2.3.1 Roofing systems

This work examines the loss impact of hail on roofs with asphalt shingles. An asphalt shingle roof system has four or five parts, illustrated in Figure 1.

- (1) Roof joists spaced between 400 mm and 600 mm apart are part of the roof truss or other structural system, supported on other structural elements in the building superstructure.
- (2) Structural sheathing such as plywood or oriented strandboard (OSB) of 8-mm to 16-mm thickness (NBC 2015 Tables 9.23.15.5-A and 9.23.16.7-A) is nailed to the roof joists with 63-mm long nails spaced at 150 mm along edges and at 300 mm in the panel zone (NBC Table 9.23.3.5-B). (US readers: 16-in to 24-in joist spacing, ¼-inch to ½-inch OSB or plywood depending on roof slope, and 8d nails at 6/12.)
- (3) One tacks on top of the structural sheathing an underlayment of asphalt-saturated paper weighing at least 0.19 kg/m<sup>2</sup> (US readers: 90-lb paper) or no.-15 asphalt-saturated felt (NBC article 9.26.6.1). The underlayment serves as a supplemental moisture barrier and prevents adhesion between the roof sheathing and the shingles. The underlayment is optional in some codes and standards, mandatory in others.
- (4) The top layer comprises overlapping layers of shingles. These are nailed to the roofing deck with four to six 10- to 12-gauge galvanized nails per shingle, and adhered to the layer below with factory-applied, heat-activated sealant bands. As shingles age, it is common to add a layer of new shingles, up to three in total on steep roofs, without removing the old layer. Placing a new layer on top of the old avoids the cost to remove and dispose of the old layer, but can introduce two problems: uneven surface and fastener strength, potentially greatly reducing the life expectancy

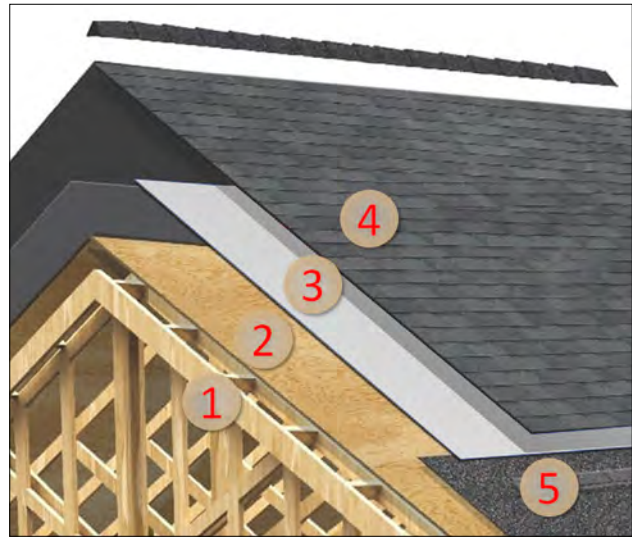


Figure 1. Parts of an asphalt shingle roof.



of the new layer. An uneven surface can result in lateral diversion of rainwater and a leak into the occupied space of the building. Poor fastener penetration (fasteners that are too short to hold new shingles down on top of those left in situ) can result in wind failures.

- (5) In some cases, add eave protection such as felt underlayment from the roof edge to 900 mm up the roof slope (NBC 2015 subsection 9.26.5).

### 2.3.2 Asphalt shingles

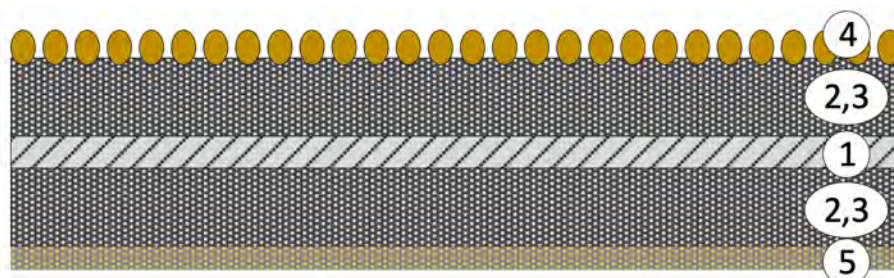
Different sources offer different categories of asphalt shingles. CertainTeed (2022) speaks of three common types: three-tab shingles, dimensional shingles, and luxury or premium shingles. Owens-Corning (2022) also speaks of three-tab and dimensional, but distinguishes subcategories of luxury or premium shingles. CSA Group's (2016) standard A123.5 uses the general terms "single or multi-tab" and "single or multi-layer" and the specific terms "dimensional," "laminated," and "overlay" to refer to the three principal shingle types.

Regardless of naming and categories, asphalt shingles generally have a flexible mat 1 m wide and 330 mm high, many with cutouts to create three tabs. Shingles are overlapped so that any spot on the roof has at least two layers of shingle for steeper roofs (slope at least 1 in 3, NBC article 9.26.7.1), and three layers for shallow-sloped roof (NBC article 9.26.8.1). Each shingle is nailed or stapled to the structural sheathing with at least four fasteners along a horizontal line at least 12 mm above the tops of the cutouts (NBC article 9.26.7.4) at the mid-height of the shingle: one nail near each end (25 mm to 40 mm from the edge; NBC article 9.26.7.4) and the others equally spaced between them (NBC article 9.26.7.4). Some shingle manufacturers require six nails or staples per shingle for some product lines.

Asphalt shingles have five components (Figure 2):

- (1) A fiberglass mat provides the shingle's strength and stiffness.
- (2) An asphalt layer serves to shed water and to adhere ceramic-coated crushed rock particles called granules.
- (3) Finely ground fillers or mineral stabilizers in the asphalt improve the asphalt's fire resistance, flexibility, durability, and resistance to weather.
- (4) The granules coat the upper surface of the shingle. They provide its color and protect the asphalt from ultraviolet light, which degrades the asphalt.
- (5) The lower (back) surface is coated with a fine mineral that prevents shingles from sticking to machinery during manufacture and each other while stored (Asphalt Roofing Manufacturers Association 2021).

**Figure 2.** Asphalt shingle cross section.



Three-tab shingles are the least expensive of the three types of asphalt shingle, and have a single layer of mat, asphalt, and granules. Dimensional shingles (also called architectural or laminate shingles) are the most common of the three. They have two or more fiberglass-and-asphalt layers that give the roof a thicker, three-dimensional appearance, and longer life. The third type, luxury or premium shingles, have two or three thicker fiberglass-asphalt-granule layers and most closely resemble traditional slates or shakes (Groom 2010).

### **2.3.3 Shingle impact rating**

Not all shingles equally resist hail. Two test standards – UL 2218 and FM 4473, discussed next – rate shingles for their resistance to impact (especially by hail) on a 1-to-4 scale, with higher numbers indicating more resistance to impact.

The UL 2218 (Underwriters Laboratory 2020) standard, *Standard for Safety Impact Resistance of Prepared Roof Covering Materials*, examines whether shingles mounted on a 12-mm plywood deck with 50 x 100 mm lumber framing and impacted by steel balls suffer visible (under 5x magnification) tears, fractures, cracks, splits, ruptures, crazing, and other evidence of opening through the cross section of the roof. Neither surface cracks that do not extend through the cross section, nor cosmetic damage (such as dents or the loss of granules) constitutes failure. A class-1 shingle survives impact from 32-mm (1.25-in.) diameter balls; class 2, 38-mm (1.5 in.); class 3, 44-mm (1.75 in.); class 4, 50-mm (2.0-in.) diameter balls. Steel balls are dropped from a height set to match the kinetic energy of a hailstone impacting the roof at terminal velocity. That is, it assumes that if a steel ball imparts the same impact energy as a falling hailstone, it will cause the same damage. The authors of UL 2218 acknowledge that “there is no currently established direct correlation between the performance of roof coverings when impacted by hailstones versus steel balls.” The test specifies no criteria related to loss of granules.

The FM 4473 (FM Approvals 2005) standard, *Specification Test Standard for Impact Resistance Testing of Rigid Roofing Materials by Impacting with Freezer Ice Balls*, offers a similar impact test but uses ice balls rather than steel, and the same 1-to-4 rating scale. That is, 1 indicates no cracking or breakage of the shingle when impacted by ice spheres with 32 mm (1.25 in.) diameter, 2 refers to 38 mm (1.5 in.), etc. Like UL 2218, the test requires the velocity of the ice ball to be set so that its kinetic energy at impact matches a specified value, the estimated kinetic energy of a hailstone at terminal velocity.

Both UL 2218 and FM 4473 tests are pass-fail. Neither tests shingles to determine the relationship between hailstone size and probability of damage (which one might call a fragility test) or degree of damage (which one might call a vulnerability test).

The Insurance Institute for Business and Home Safety (2019) has introduced a new test protocol, the IBHS Impact Resistance Test Protocol for Asphalt Shingles, that more closely approaches a fragility or vulnerability test. The test more closely simulates real hailstones of 38 and 50-mm diameters, which are propelled onto shingles mounted on a realistic roofing system with prescribed kinetic energy. Performance is measured in terms of three damage outcomes: a subjective degree of breach severity (meaning tears, ruptures, or cracks), deformations (two measures of dent volume), and the area over which at least one granule was lost. The measures of the three outcomes are averaged and the result is a number between 0 and 3 called an average severity score, where 0 is least damaged and 3 is most damaged. The 0-to-3 range is discretized into four performance ratings from excellent (0 to 0.3) to poor (greater than 1.8).

Brown-Giammanco et al. (2021) explain the new IBHS test, needed partly because of differences between natural hailstones and test spheres in their kinetic energy, mass, velocity, momentum, compressive strength, and other test parameters that cause steel and ice-ball test spheres to produce more damage than does hail.

As part of ICLR's HailSmart™ program, ICLR (2018) has advocated for the installation of Class 4 impact resistant roofing that meets UL 2218 for all homes located in regions of moderate or high risk of hail, such as in southern Alberta and southern Saskatchewan. ICLR also advises that when re-roofing to install full roof underlayment, preferably self-adhering waterproofing underlayment (a.k.a. ice-and-water shield).

While ICLR advocates for class-4 shingles, the Insurance Institute for Business and Home Safety (2020) considers any shingle product rated as class 3 or 4 by the UL 2218 or FM 4473 testing program to be impact-resistant (IR, though IBHS uses the term impact-rated), and refers to all others as non-IR.

#### ***2.3.4 Some common lines of impact-resistant shingles***

Roof shingle material prices and availability vary by brand and product. Table 1 lists some leading brands of impact-resistant shingles and a recent (as of this writing) material price, excluding GST and HST. It also shows some non-impact-resistant shingles for price-comparison purposes. The table shows unrated shingles, three class-3 products, and 14 class-4 products. Several products are available through retail outlets and their prices are readily available to the public. Many products are only distributed to building professionals. Their prices are not public, and may vary substantially between markets. Prices can be difficult to compile, so no attempt has been made to include all shingle types, manufacturers, or product lines in Table 1.

The least expensive impact-resistant roof costs about the same as a non-IR roof: BP Canada's Mystique FM 4473 class-3 rating adds little if any material cost relative to, say, the Everest line. BP's Manoir line, also class 3, costs more but BP Canada's marketing materials emphasize Manoir's greater wind and water protection to distinguish it from the other lines.

Class-4-rated shingles appear to start at \$160 per square: CertainTeed Landmark IR (\$155 per square) and Owens Corning TruDefinition Duration (\$167 per square). Prices for other class-4 shingles reach \$340 per square (Tamko Stormfighter IR). Some offer other monetarily valuable features, such as algae or wind resistance or solar reflectivity.

**Table 1.** Some common lines of impact-resistant shingles.

| Manufacturer  | Line                          | Rating     | Matl price (CAD/sq) | Price source, comment          |
|---------------|-------------------------------|------------|---------------------|--------------------------------|
| BP Canada     | Dakota                        | None       | \$96                | RONA.ca                        |
|               | Everest                       | None       | \$99                | RONA.ca                        |
|               | Yukon                         | None       | \$93                | RONA.ca                        |
|               | Mystique                      | FM class 3 | \$99                | RONA.ca                        |
|               | Manoir                        | FM class 3 | \$142               | RONA.ca                        |
|               | Vanguard                      | UL class 4 | \$188               | Proline Construction, Edmonton |
| GAF           | Marquis Weathermax            | None       | \$85                | Home Depot Calgary             |
|               | Timberline HDZ                | None       | \$92                | Ditto                          |
|               | Timberline ArmorShield        | UL class 4 | \$267               | Hanscomb Ltd (2020)            |
|               | Grand Sequoia IR              | UL class 4 | N/A                 | No distributor found           |
| IKO           | Nordic                        | FM class 4 | \$207               | Roofmart, London, ON           |
| Tamko         | Stormfighter IR               | UL class 4 | \$340               | Hanscomb Ltd (2020)            |
| Malarkey      | Vista AR                      | Class 3    | \$220               | Hanscomb Ltd (2020)            |
|               | Legacy                        | Class 4    | \$267               | Hanscomb Ltd (2020)            |
| Owens Corning | TruDefinition Duration        | Class 4    | \$167               | Menards.com, Home Depot        |
|               | TruDefinition Weatherguard HP | Class 4    | \$260               | Hanscomb Ltd (2020)            |
| CertainTeed   | Landmark IR                   | UL class 4 | \$155               | Hanscomb Ltd (2020)            |
|               | Northgate IR                  | UL class 4 | \$205               | Hanscomb Ltd (2020)            |
|               | Landmark Solaris Gold IR      | UL class 4 | N/A                 | No distributor found           |
|               | Presidential Shake IR         | UL class 4 | N/A                 | No distributor found           |
|               | XT 30 IR                      | UL class 4 | N/A                 | No distributor found           |
|               | Highland Slate IR             | UL class 4 | N/A                 | No distributor found           |

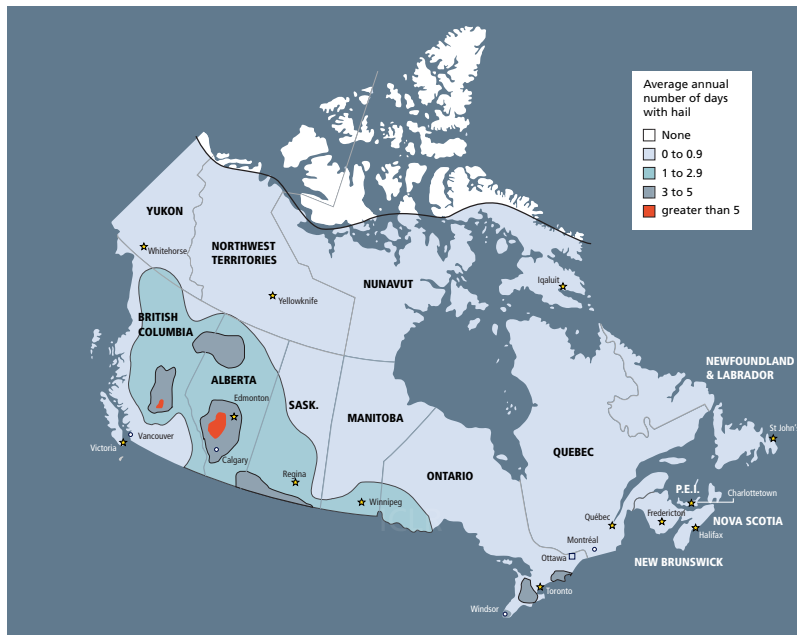
## 2.4 Hazard

Let us now summarize some of the most relevant literature on hail hazard. Here, hazard means the frequency of hailstorms at a chosen location, the number of hailstones that strike an area of a given size, the distribution of hailstone size, and the effect of climate change on hailstorm frequency.

### 2.4.1 Hail formation, physical properties, and terminal velocity

First, for the newcomer to hail risk, let us review the nature of hail. The American Meteorological Society (2012) and Raupach et al. (2021) both provide useful summaries of the formation of hail. Hail consists of solid ice that forms in thunderstorms in convectively unstable atmosphere.

By convention, hail has a diameter of 5 mm or more; smaller particles are classified as ice pellets or snow pellets. Hailstones form when raindrops are carried upward by strong updrafts (over 15 m/sec) into extremely cold areas of the atmosphere and freeze. They grow by falling into warmer air and colliding with liquid water drops that freeze onto the hailstone's surface. The cycle can repeat many times, enlarging the hailstone with each cycle. Hail also melts as it falls through warmer surface air. More on that point later.



**Figure 3. Average annual number of days with hail (ICLR 2018).**

It is generally believed that hail causes damage roughly in proportion to its kinetic energy just before it impacts an object such as a roof. Thus, its terminal velocity matters. Bilham and Relf (1937) estimated a relationship between the terminal velocity of hailstones and their diameter based on the observed drag coefficient of spheres towed by aircraft, density of air, density of hailstones (from 0.4 to 0.92 g/ml), and the bimodal relationship between drag coefficient and Reynolds number (a factor that only matters for spheres larger than about 7 cm diameter).

Several authors (e.g., Laurie 1960, on which prior versions of UL 2218 were based) assumed Bilham and Relf’s derived terminal velocities. They appear to be overestimated. Heymsfield et al. (2014) measured the physical properties of 2,295 natural hailstones (maximum dimension, mass, and cross-sectional area), offering size-dependent relationships for terminal velocity and kinetic energy. They found the Bilham and Relf (1937) estimates of kinetic energy overestimated by about 50%. UL 2218 has been revised accordingly.

NOAA’s National Severe Storms Laboratory (ND) reports that small hailstones (less than 25 mm diameter) fall between 15 and 40 km/hr. Hailstones between 25 mm and 50 mm diameter fall between 40 and 65 km/hr. Hailstones between 50 and 100 mm in diameter fall between 65 and 115 km/hr. Very large hailstones with diameters exceeding 100 mm may fall at over 160 km/hr. Hailstones have been observed with diameters of 200 mm and weight approaching 900 g. For comparison, a strong baseball pitcher can throw a fastball at 160 km/hr; a baseball has a 75 mm diameter and weighs about 145 g.

#### **2.4.2 Hailstorm frequency**

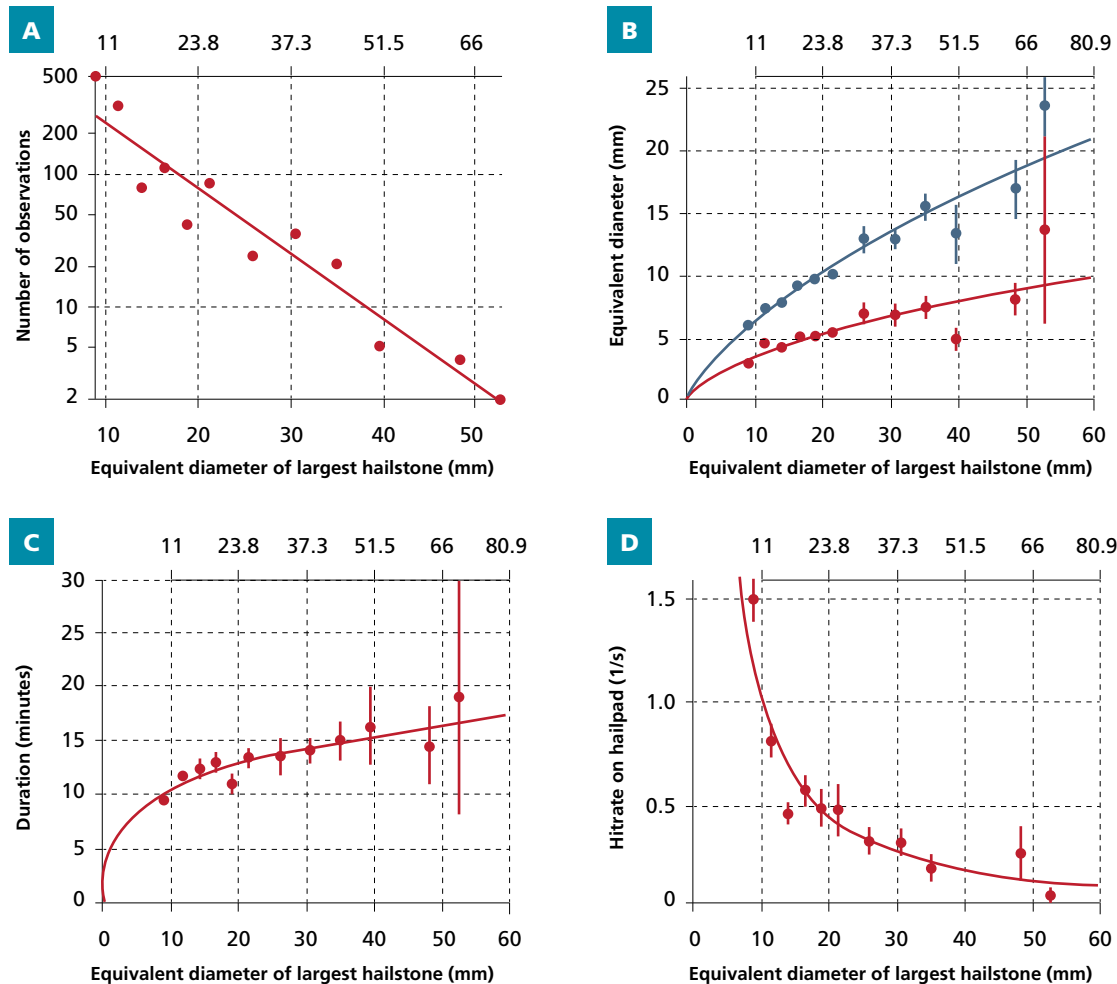
In Canada, Hailstorm Alley refers to an area of south and central Alberta where hailstorms occur 3 or more times annually (Figure 3). Calgary has experienced four hailstorms since 1991 that cost over \$250 million in damage (Mann 2021, Canada Press 2014). Cecil and Blankenship (2012) provide a global analysis of severe hail frequency per year per 500 km<sup>2</sup>.

Etkin (2018) investigates Canadian hail climatology data: monthly hail days at 3,600 hail observing stations during the period 1977 to 2007. (After 2007, the number of hail observation stations dropped precipitously, so recent data are largely unavailable.) Etkin offers temporal trends of hail days per station per season (May to September), and a spreadsheet that estimates hail frequency for any geographic location within the area covered by the stations. For example, the spreadsheet estimates that the Sherwood neighborhood of north Calgary currently experiences 2.35 hail days per year. He cautions that topography matters but is not reflected in the data.

### 2.4.3 Hailstorm hitrate and duration (volume or count per square metre)

Grieser and Hill (2019) used 37,000 crowdsourced observations from the United States and Canada of hail diameter, duration, and number density, along with an assumed exponential distribution of hailstone size aloft, to model hail intensity. They observe that maximum hailstone size on the ground  $D_L$  followed an approximately exponential distribution, as shown in Figure 4A. They also offer relationships between  $D_L$  and a variety of other useful hazard measures. Notable here are average hailstone diameter ( $D_A$ ), the blue line in Figure 4B, hitrate (number of hailstones per square metre per second) and duration. The data come from the US-based Community Collaborative Rain, Hail and Snow Network (CoCoRaHS). The authors validated their results by comparison with hailpad observations of the largest hailstone diameters and hail kinetic energies in southwestern France. Note that their tabulated functions and parameter values for duration and hitrate do not seem to match their figures.

**Figure 4.** (A) Number of observations exceeding minimum equivalent diameter of largest hailstone, (B) average (blue) and smallest (red) diameter, (C) duration, and (D) hitrate as functions of equivalent diameter of largest hailstone. The upper x-axis shows maximum diameter of the largest hailstone in mm (Grieser and Hill 2019).



#### 2.4.4 Hailstone size distribution

Hailstone size distribution matters because damage strongly relates to the hailstone's kinetic energy when it impacts a damageable asset, and kinetic energy increases approximately with the fourth power of diameter. A hailstone 50 mm (2 inches) in diameter when it strikes the ground has 16 times the kinetic energy and damage potential of a hailstone 25 mm (1 inch) in diameter (because it is 2 times the diameter, and  $2^4 = 2 \times 2 \times 2 \times 2 = 16$ ).

Wong et al. (1987) obtained hailstone samples with mobile sampling vehicles from five Alberta storms in 1980 and 1982. They photographed hailstones, calculated their equivalent-volume diameters in size intervals of 1 mm, and found that that hailstone sample size can be idealized with a shifted gamma distribution, the shift reflecting data truncation of the data at some minimum size such as the conventional 5 mm minimum diameter for a particle to be considered hail. The distribution has three parameters. First, the lower truncation point  $a$ , which could in principle be set to 0 for purposes of simplicity, and because one can ignore values of less than 5 mm. Second, a shape parameter  $\alpha$ . Their samples reveal median values of  $\alpha \approx 2.0$  to 1.75, with the smaller value corresponding to a longer sampling duration (about 5 minutes). Third, an inverse scale parameter  $\beta$ , which relates to the average hailstone diameter  $D_A$  as shown in equation (1).

$$D_A = \frac{\alpha}{\beta} \quad \alpha \approx 1.75 - 2.0 \quad (1)$$

Fraile et al. (2003) offer probability distributions for the diameter of hailstones that reach the ground, accounting for melting while the hailstones fall. They too suggest a gamma distribution for diameter. They estimate that about 8% of hailstones inside a cloud actually reach the ground. They reiterate the cumulative distribution function of the gamma distribution, which one can use to estimate the fraction of hailstones on a hailpad (or other surface such as the horizontal projection of a roof) of any range of hailstone sizes.

Etkin (2018, Table 1) suggests that at least in central Alberta, approximately 10% of hailstorms (5.2 days out of 52.4 hail days) produce hailstones larger than 33 mm in diameter.

#### 2.4.5 Climate change

Cao (2008) examines the correlation between increasing frequency of hailstorms in Ontario and warming air temperatures. He finds a roughly linear increase in storm frequency across the province from about 14 events in 1979 to about 29 in 2002, during which time mean temperatures have increased about 0.7C in Thunder Bay (2.9C to 3.5C), Sudbury (4.2C to 5.1C), and London (7.7C to 8.6C). Maximum temperatures have also increased about 0.8C: Sudbury (9.5C to 10.3C), Thunder Bay (9.3C to 9.9C) and London (12.5C to 13.6C).

ClimateData.ca (2021), a consortium of six public entities, nonprofits, and research institutions, offers authoritative projections for various climate metrics. Among these: future precipitation by geographic location under each of three representative concentration pathways. For example, both for Calgary, AB and Regina, SK, ClimateData.ca estimates a fairly constant number of wet days per year (>1 mm, >10 mm, and >20 mm) under RCPs 2.6, 4.5, and 8.5. Its climate estimates do not distinguish between rain, snow, and hail.

Rauchpach et al. (2021) examined the expectation that atmospheric ingredients for hail – an unstable atmosphere, the melting of falling hailstones, and wind shear – would change with a warming climate. They estimate more water vapour in the future atmosphere: 7% per 1C warming, which leads to greater convective instability and stronger updrafts, and can increase hail precipitation rates and produce larger hailstones. However, warming also increases the thickness of the warm layer near the ground, accelerating melting as hailstones drop through the warm layer. They conclude that in the Canadian Rockies, “Across the whole year, an increase in the number of hail days is predicted, with increases of 7%, 21% and 146% for severe [20 mm], large [35 mm], and very large hail [50 mm].” They estimate a decrease in convective storms and severe hail in the eastern USA (they do not mention eastern Canada).

#### **2.4.6 Hail seeding**

This analysis ignores the effect of hail seeding. However, the reader may find a brief explanation of seeding useful. In concept, hail seeding accelerates the formation of hailstones by providing a supply of nuclei (e.g., grains of silver iodide or dry ice) onto which supercooled liquid can freeze. More hail embryos compete for the available supercooled water in the cloud, producing more, but smaller, hailstones. Furthermore, smaller hailstones melt more readily as they drop through the warm air near the ground. That happens because smaller hailstones have a higher surface-to-volume ratio than larger ones. To explain: heat gain increases with surface area (related to the square of diameter) while the volume of ice that has to melt increases with the cube of diameter. A higher surface-to-volume ratio means the smaller hailstones gain heat faster per unit volume than their larger siblings. So, in a hailstorm with smaller hailstones, more precipitation melts and falls as rain rather than hail.

### **2.5 Fragility functions and derivation methods**

It will be necessary here to derive and use fragility functions, so this short section introduces the newcomer to performance-based engineering. In performance-based earthquake engineering, a fragility function refers to a functional relationship between the occurrence probability of some undesirable outcome (such as the probability that a hailstone will cause visible cosmetic damage to a shingle or break its moisture barrier) and some measurable degree of environmental excitation (such as the kinetic energy imparted on the shingle by the hailstone impact).

Several authors offer methods to derive fragility functions from empirical evidence and engineering first principles, e.g., US Nuclear Regulatory Commission (1975), Kennedy and Ravindra (1984), and Swan and Kassawara (1998). Porter et al. (2007) bring these into a single coherent framework for use in FEMA P-58's (Applied Technology Council 2012) second-generation performance-based earthquake engineering guidelines, and add treatment of expert opinion and Bayesian updating. Porter et al. (2007) offer methods with which to derive parametric probability distribution functions to represent fragility, with an emphasis on lognormal cumulative distribution functions, because of several theoretical and practical advantages the lognormal offers.

Porter et al. (2007) and FEMA P-58 (Applied Technology Council 2012) deal with an important fragility issue that will arise here: empirical methods can underestimate variability in the capacity of real specimens. That can happen when the available evidence come from a few samples, or from samples that are more homogenous than the population they are intended to represent, or that were subjected to loading conditions that do not represent the variability of loading condition in nature. They offer tests to judge whether to increase variability and how to do so, generally by increasing variability by a prescribed amount and fixing a point on the fragility function at a low probability, e.g., the 10<sup>th</sup> percentile, to avoid biasing the annualized failure rate.



## **2.6 Damage and loss**

### **2.6.1 Hail impact physics**

**Size threshold to cause damage.** The US National Weather Service (2010) issues severe thunderstorm warnings based in part on hail reaching 25 mm (1 inch) in diameter, with a belief that “significant damage does not occur until hail size reaches 1 inch in diameter.” It cites in part assertions from “core partners in emergency management and the media” that thunderstorm warnings issued for smaller hail diameters “might have desensitized the public to take protective action during a severe thunderstorm warning.”

**Contact force.** Perera (2017, 2018) argues that hail piercing damage to building roofs and cladding depends on the maximum instantaneous contact force (that between the hailstone and the surface it impacts) as opposed to the reaction force (between the surface and the surrounding structure). In performance-based earthquake engineering, one would use the contact force as the engineering demand parameter, that is, the output of structural analysis and input to a fragility function for the roofing, siding, glazing, or other damageable component. Note that contact force is not the same thing as kinetic energy.

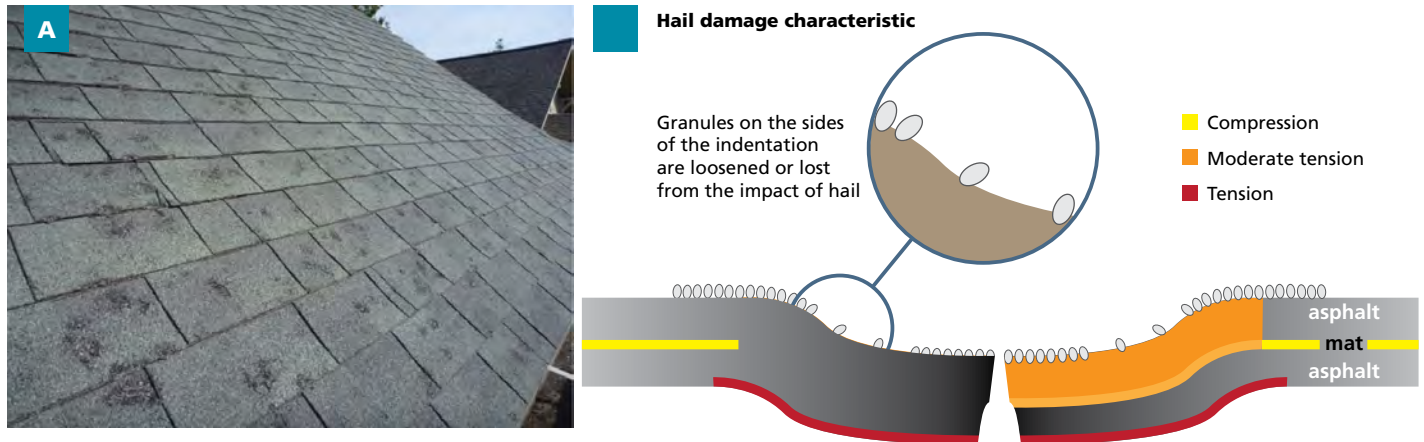
**Transfer of kinetic energy.** Hailstones have a low coefficient of restitution, COR, compared with a baseball – they are harder. Baseballs have a COR about 0.3 when struck with an aluminum bat. In experiments, Sun et al. (2015) found that a 50 mm spherical hailstone weighing about  $m_1 = 60$  g, impacting at relative velocity  $v_0$  between 7 and 28 m/sec (25 to 100 km/hr) normal to the flat end of a 2.16-kg steel cylinder target mounted on a 53 kN/m spring whose axis aligns with target cylinder and hailstone trajectory has a coefficient of restitution between 0.02 and 0.04 – higher for a lower-velocity impact. A low number means more of the hailstone’s kinetic energy is transferred to the target, which causes more damage. Contact forces varied between 1 kN and 7 kN depending on velocity, with the lower value corresponding to 8 m/sec (29 km/hr) and the higher with 32 m/sec (115 km/hr). The authors offer a simple analytical model of maximum contact force that depends on coefficient of restitution COR, hailstone velocity  $v_0$ , and spring stiffness  $k_n$ .

### **2.6.2 Damage symptoms**

Hail impact causes up to four main symptoms of damage: (1) dislodged granules at the point of impact, (2) discoloration because of the lost granules, (3) permanent deformation of the shingle – a shallow pit where the hailstone struck – and (4) tearing of the shingle. Shingle tears also allow water penetration, which can manifest through water damage to the roofing and ceilings. Damage can be hard to see from the ground for hailstones smaller than the diameter of a golf ball (about 40 mm). See Figure 5.

**Figure 5. (A)** A hail-damaged roof, showing discoloration because of the loss of granules.

**(B)** Illustration of hail damage. Source: Roofingcalc.com (2021), usage claimed under fair-dealing doctrine. (© 2009 InterNACHI).



### 2.6.3 Asphalt shingle hail fragility

Marshall et al. (2002) review roof hail-damage testing protocols since 1952, focusing on tests that propelled frozen tap water ice spheres of various diameters to perpendicular impact with various roofing systems at approximately free-fall terminal velocity. Table 2 recaps their test results. The authors define damage to include “punctures, tears, or fractures (bruises) in the shingle mats as well as the displacement of granules to visibly expose the underlying bitumen.” The authors assert that hail damage to 3-tab roofing shingles begins when simulated hailstones reach or exceed 25 mm (1-in.) diameter. But their data show that 5 of ten tests of 3-tab organic shingles experienced damage when impacted by 25-mm (1-in.) diameter spheres at terminal velocity, and 90% experience damage when impacted by a 32-mm (1.25-in.) sphere. None of the 10 specimens were damaged by a 20-mm sphere, suggesting 5% or lower failure probability with 20-mm spheres.

**Table 2.** Marshall et al. (2002) ice-ball impact tests of various roofing products.

| Type of roofing product   | Age (yr) | Fraction of specimens damaged by ice ball impacts |       |       |       |       |       |
|---------------------------|----------|---|-------|-------|-------|-------|-------|
|                           |          | 20 mm   | 25 mm | 32 mm | 38 mm | 44 mm | 50 mm |
| 3-tab fiberglass shingles | 11       |   | 0%    | 60%   | 90%   | 100%  | 100%  |
| 3-tab organic shingles    | 11       | 0%  | 50%   | 90%   | 100%  | 100%  | 100%  |
| 30 yr. laminated shingles | 11       |   | 0%    | 0%    | 60%   | 90%   | 100%  |
| Cedar shingles            | 11       |   | 0%    | 30%   | 80%   | 100%  | 100%  |
| Heavy cedar shakes        | 0        |   | 0%    | 0%    | 50%   | 90%   | 100%  |
| Fiber-cement tiles        | 0        |   | 0%    | 20%   | 80%   | 100%  | 100%  |
| Flat concrete tiles       | 0        |   | 0%    | 20%   | 50%   | 50%   | 100%  |
| S-shaped concrete tiles   | 0        |   | 0%    | 0%    | 0%    | 0%    | 80%   |
| Built-up gravel roofing   | 8        |   | 0%    | 0%    | 0%    | 0%    | 30%   |

Marshall et al. (2004) examine the definition of hail damage to asphalt shingles. They illustrate the differences among hail damage, manufacturing defects, construction defects, and intentional mechanical damage (people damaging roofs to try to mimic hail damage). Although they acknowledge that “As asphalt shingles age, their components break down,” they find that the way hailstorms only modestly reduce granules “does not shorten the life of the roof or adversely affect its water shedding ability as long as the impacted areas are not bruised or punctured, and remain covered with granules.”

In a short white paper on hail damage to asphalt shingles, Haag Engineering Co. (2006) equates “diminution in water-shedding capability” with “a fracture in the shingle” that is “always ... detectable in the bottom side of a shingle.” The authors indirectly equate dislodged granules with fracture: “For shingles in relatively good condition with remaining service life, a hailstone capable of dislodging granules and exposing the coating bitumen necessarily fractures the reinforcement of the shingle and generates a detectable bruise.” Strangely, they go on to assert that “when a shingle is struck by a hailstone dislodging granules and exposing coating bitumen while the underlying reinforcement remains intact, the shingle necessarily must be defective or else is nearing or has exceeded its expected service life.” But they offer no evidence to demonstrate that condition with diminution of water-shedding capability.

Haag Research & Testing (2020) studied the effectiveness of roof-shingle impact tests: UL 2218 and ANSI/FM 4473, in which one impacts shingles with steel balls and ice spheres, respectively, and then visually examines them for damage. The authors performed the standard tests and then examined the tested shingles more closely, by “dissolving the asphalt or modified asphalt bitumen from the shingles. This allowed the shingle reinforcements to be examined for fractures or strains caused by the impacts without hand manipulation which can initiate damage.” They found that most shingles that appeared to pass the requirements of visual examinations after standard tests had hidden damage to the shingle reinforcement, the fiberglass mat, even under class-1 testing. The authors did not test the shingles for whether impacted shingles continue to shed water.

#### **2.6.4 Asphalt shingle repair cost**

Marshall and Herzog (1999) offer a hail damage assessment protocol, in which one examines at least one roofing square – that is, a 3.05 m by 3.05 m (10 ft. by 10 ft.) square – on each slope of a roof. They define hail-caused damage to an asphalt shingle in roofing as “[1] rupture of the reinforcing mat or [2] displacement of granules sufficient to expose underlying bitumen.” (In later work they found that loss of granules does not reduce the life or effectiveness of the shingle.) Rupture of the reinforcing mat “involves either bruising, which can be felt as a soft spot on the shingle (much like an apple bruise), or puncturing where there is a hole in the mat. Bruises are soft areas large enough to be detected by finger pressure and generally are accompanied by a sufficient loss of granules within the impact area to expose the underlying bitumen.

Marshall and Herzog (1999) also offer an equation for  $C$ , the cost to repair hail damaged roofing, as the product of  $D$  (the number of damaged shingles per roofing square),  $U$  (the unit cost to repair a shingle),  $R$  (a factor to account for repair difficulty), and  $A$  (area of the roof in roofing squares). They suggest including a factor of 1.1 to 1.2 in  $U$  to account for waste.

The Insurance Institute for Business and Home Safety (2020) reports on a cost survey across US markets of the material cost of asphalt shingles per roofing square. The authors found that impact-resistant shingles cost between 2% and 9% more than non-impact-resistant shingles, with the smaller cost differences in places with more availability of impact-resistant shingles (Oklahoma City and Dallas-Fort Worth), where hail is more common.

Several sources provide information about roof repair costs. One of the more accessible sources is RSMMeans (e.g., 2020, p. 73). For example, that source estimates the labour cost (including approximately 76% overhead and profit, p. 321) to demolish and install 30-year architectural laminated shingles at \$146 per square for material cost plus \$117.50 per square for labour, to which one would

add goods and service tax or harmonized sales tax (e.g., 5% in Alberta). RSMeans (2020, p. 299) also offers a factor to account for geographic location, e.g., in Calgary, 1.07 times the North American average, including the USD-CAD exchange rate. Thus, using RSMeans' costs, Calgary roof repair could cost about \$296 per roofing square, or \$31.87 per m<sup>2</sup>, or \$9.00 per shingle. This figure omits any required costs to repair the roof deck. It can fluctuate over time with material and labour prices.

### **2.6.5 Depreciation**

At least some insurers depreciate claim payments as the roof ages. One insurer depreciates claim payments by 45% if the damage occurs 15 years after the roof is installed, and another 3% per year thereafter up to a maximum of 75% (written commun., V. Lavigne, Directrice principale, Desjardins, February 10, 2022).

### **2.6.6 Incentives to promote mitigation**

Who gains and who loses when a developer or homeowner installs an impact-resistant roof on a house, or undertakes any other remediation measure that adds cost? Who pays for the remediation, is the initial cost transferred to later buyers through higher resale value, and to what extent does each stakeholder benefit from avoided losses?

Multi-Hazard Mitigation Council (2020) identifies several stakeholders: the developer, owner, tenant, and insurer. A sequence of owners, tenants, and insurers are probably involved. That work points out the costs and benefits are unequally shared among stakeholders. The owner at the time of the work bears the cost. Possibly the owner recoups the cost through higher resale value, as suggested by several authors: Simmons et al. (2002), Simmons and Sutter (2007), Awondo et al. (2016, 2019), and Porter et al. (in press). The insurer enjoys avoided property repair costs if the house is insured. The sequence of owners might enjoy lower insurance premiums if the insurer reduces the premium to reflect the lower risk. The series of owners enjoy lower nuisance costs when hail damage occurs: less time lost dealing with the claim and with contractors.

The authors of Multi-Hazard Mitigation Council (2020) argue that the various stakeholders' often-misaligned interests hinder the uptake of mitigation measures that make sense from a societal viewpoint. They suggest a set of financial incentives that would reallocate mitigation cost among the stakeholders, better aligning their interests with those of society as a whole, which (they speculate) would increase uptake of mitigation measures like impact-resistant roofing. The incentive options that are most relevant here include:

- Insurance premium reductions to reflect the insurer's lower risk. For example, the California Earthquake Authority (2021) offers a premium discount on earthquake insurance of up to 25% for retrofitting older houses and manufactured homes, which can amount to \$400 per year for an older, single-family dwelling.
- Government grants, loans, and regulatory advantages. For example, the City of Calgary offers a \$3,000 rebate for installing impact-resistant roofing (City of Calgary 2022). The State of California has offered various grants and low-interest loans to encourage retrofit as well (California Residential Mitigation Program 2020; Federal Emergency Management Agency 1994, p. 88).
- Real estate marketing material that highlights the value of a resilience measure. Such material could draw on the aforementioned work by Simmons, Awondo, and others.

### 3. Proposed methods

With the foregoing literature as a foundation, let us now consider a performance-based methodology to estimate the costs and benefits of impact-resistant asphalt shingle roof cover.

#### 3.1 Performance-based engineering

This work adapts second-generation performance-based earthquake engineering (PBEE-2, e.g., Porter 2003) for hail risk analysis. In PBEE-2, one estimates the future probabilistic performance of a building, bridge, or other single, clearly defined asset subjected to some uncertain environmental excitation such as earthquake ground shaking. One can measure performance in terms of repair costs, life-safety impacts, or loss of function (“dollars, deaths, and downtime”), propagating all major sources of uncertainty through the four analytical stages illustrated in Figure 6. These are briefly summarized here, and detailed in later sections.

The asset is defined by its location, geometry, engineering attributes, and exposed values such as replacement cost new and number of occupants. For example, one could define the asset as an average-sized new single-family dwelling in northern Calgary.

Given its location, one performs a hazard analysis, whose product is an estimate of the frequency with which various levels of some environmental intensity measure ( $H$ ) occurs. That frequency is denoted here by  $G(H)$ , where  $G$  denotes mean exceedance frequency in events per unit time. In earthquakes,  $H$  might measure the level of peak ground acceleration. Here, the  $H$  will simply denote the occurrence of a hailstorm, a binary variable.

In PBEE-2, one commonly uses nonlinear dynamic structural analysis to estimate a vector measure of structural response  $R$ , (e.g., peak floor accelerations and drift ratios) conditioned on various levels of the seismic intensity measure. Here,  $R$  will denote a vector of the probabilistic attributes of the hail field. By “probabilistic attributes of the hail field,” we mean the area density of hailstones reaching the ground (that is, the number per square metre during the storm duration) and their size distribution (that is, the probability density function of the equivalent diameter). In concept, the analysis looks like equation (2), where  $G(H)$  denotes the frequency with which hailstorms occur,  $P[R|H]$  denotes the probability of exceeding some level of  $R$  given the occurrence of a hailstorm, and  $G(R)$  denotes the frequency with which  $R$  is exceeded. In practice, we will use Monte Carlo simulation to estimate the frequency of many vector values of  $R$ .

$$G(R) = P[R|H]G(H) \quad (2)$$

In the damage analysis, one estimates the rate at which various degrees of physical damage of asset components occur,  $G(D)$ , where  $D$  denotes a vector damage measure. For the present analysis,  $D$  denotes a scalar damage measure: the number of roof shingles damaged to the extent that they must be replaced. One applies the theorem of total probability to estimate  $G(D)$  for various levels of  $D$  by integrating over all levels of  $R$ , using a fragility function  $P[D|R]$  that denotes the probability of exceeding  $D$  given a specific level of  $R$ . In concept, the integral looks like equation (3), though in practice, because  $R$  is a complex vector rather than a scalar, one might apply numerical integration in the form of Monte Carlo simulation to estimate  $G(D)$ .

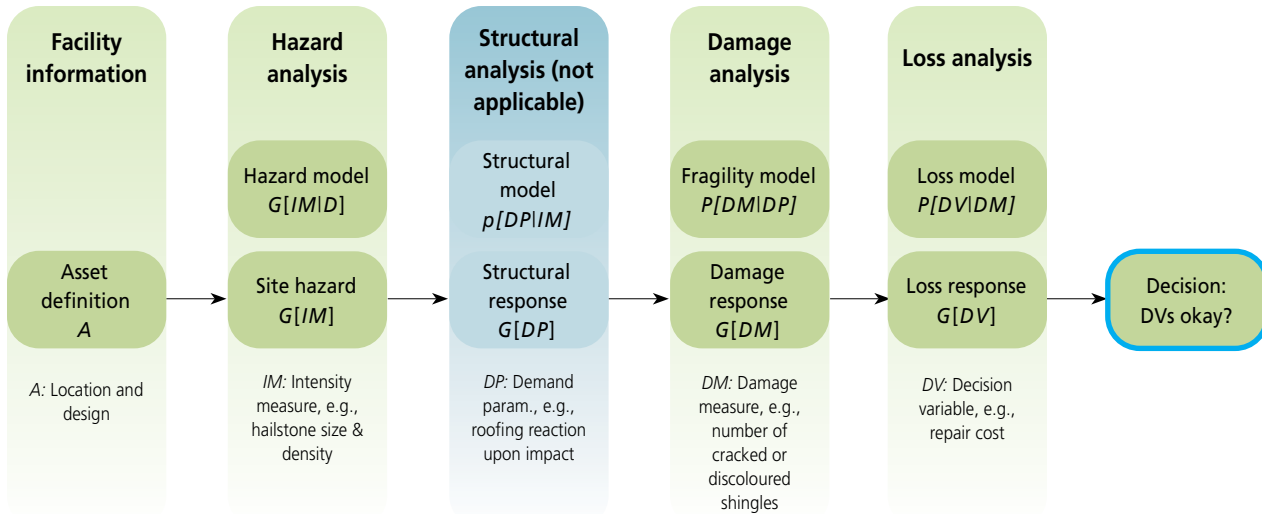
$$G(D) = \int_{R=0}^{\infty} P[D|R] \left| \frac{dG(R)}{dR} \right| dR \quad (3)$$

In the last analytical stage, the loss analysis, one estimates the frequency with which various levels of loss occur,  $G(L)$ , where  $L$  denotes a scalar or vector decision variable. In the present analysis,  $L$  will measure repair cost in 2021 CAD. Then  $G(L)$  is the frequency with which the asset suffers various levels of roof repair costs. Again applying the theorem of total probability, one estimates  $G(L)$  for various levels of  $L$ . Conceptually that looks like equation (4), but one might use Monte Carlo simulation to evaluate  $G(L)$ .

$$G(L) = \int_{D=0}^{\infty} P[L|D] \left| \frac{dG(D)}{dD} \right| dD \quad (4)$$

One can repeat the analysis under two or more conditions to quantify the effect of some change in design. Here, we will analyze a house with unrated shingles or impact-resistant shingles. Let us denote by  $G(L)$  the mean frequency with which the house with unrated shingles experiences various repair costs and  $G'(L)$  denotes the same thing but with impact-resistant shingles.

**Figure 6.** Second-generation performance-based earthquake engineering framework.



We estimate the expected annualized loss (denoted by  $EAL$ ) for each case by equation (5). Let  $EAL$  and  $EAL'$  denote expected annualized repair costs with unrated and impact-resistant roofs, respectively. Then the benefit  $B$  of choosing impact-resistant rather than unrated shingles is given by the present value of the reduced future losses, as in equation (6). In the equation,  $r$  denotes the discount rate, and  $\tau$  denotes a planning period during which one recognizes the benefit.

$$EAL = \int_{L=0}^{\infty} L \left| \frac{dG(L)}{dL} \right| dL \quad (5)$$

$$B = (EAL - EAL') \frac{(1 - e^{-r\tau})}{r} \quad (6)$$

Finally, the benefit-cost ratio is given by equation (7), in which  $C$  denotes the incremental cost of installing class-4 rather than unrated roof shingles.

$$BCR = \frac{B}{C} \quad (7)$$

This covers the general concept. Let us now consider the details.

### 3.2 Asset definition

We are interested in hail mitigation for the roofs of single-family dwellings. We define our asset using the average roof area of a statistical sample of 102 single-family dwellings in Canada (Porter et al. 2021). Let us place the sample house in a large city in Hailstorm Alley.

### 3.3 Hazard analysis

Let us quantify hazard with five parameters:

1. Geographic location, selected during the asset definition
2. Time  $t$ , meaning the duration in years over which we recognize the benefit.
3. Frequency of hailstorms,  $f_h(y)$ , the mean number of events per year in year  $y$ . Frequency is implicitly conditioned on location and a set of deterministic, fixed assumptions about climate change. Let us take  $f_h(2022)$  from Etkin (2018), as illustrated in Figure 7.
4. Hailstone area density  $R$ , an uncertain (i.e., random) number of hailstones per square metre conditioned only on the occurrence of a hailstorm at the selected geographic location. Let us assume that  $R$  is a stationary random variable and will not change over time. This variable might depend on hailstone seeding, which we ignore here.
5. Hailstone diameter  $D$ , an uncertain (i.e., random) variable, assumed to be independent and identically distributed between hailstones, conditioned on the occurrence of a storm. This variable might depend on hailstone seeding, which we ignore here.

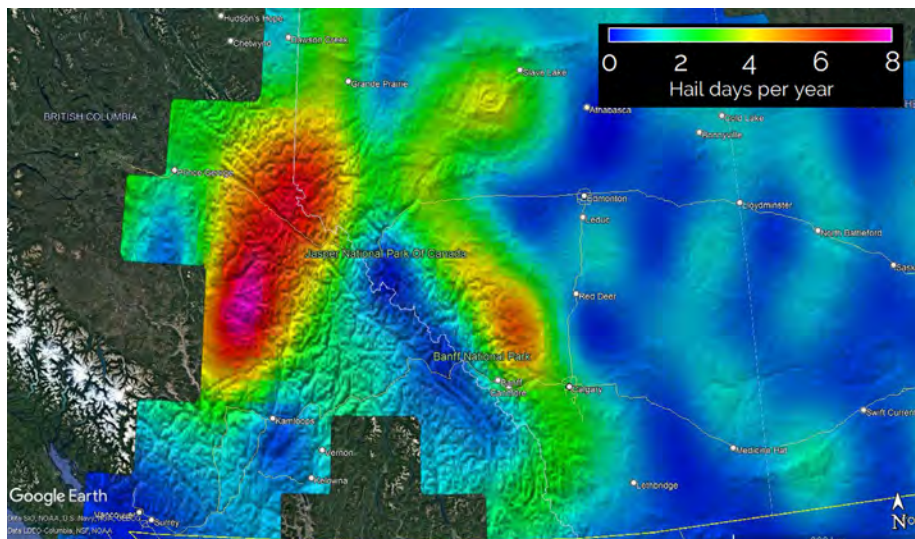


Figure 7. Hailstorm frequency in 2021, denoted by  $f_h(2021)$ , after Etkin (2018).

Conditioned on the occurrence of a hailstorm, one can apply Grieser and Hill's (2019) observations of maximum hailstone diameter (Figure 4A) to estimate cumulative distribution function of equivalent diameter of the largest hailstone  $D_L$ , in mm. The line in Figure 4A takes the form of Equation (8). The cumulative distribution function of  $D_L$  can then be estimated as shown in equation (9) and illustrated in Figure 8. In the equation,  $m_{D_L}$  is the slope of the line in Figure 4A, and  $b_{D_L}$  is its  $y$ -intercept, both in natural-log space. Equation (10) gives the probability density function. One can rearrange equation (9) to provide an estimate of the value of  $D_L$  associated with non-exceedance probability  $p$  as shown in equation (11).

$$nObs(x) = \exp(m_{D_L} \cdot x + b_{D_L})$$

$$m_{D_L} = 0.111 \text{ mm}^{-1} \quad (8)$$

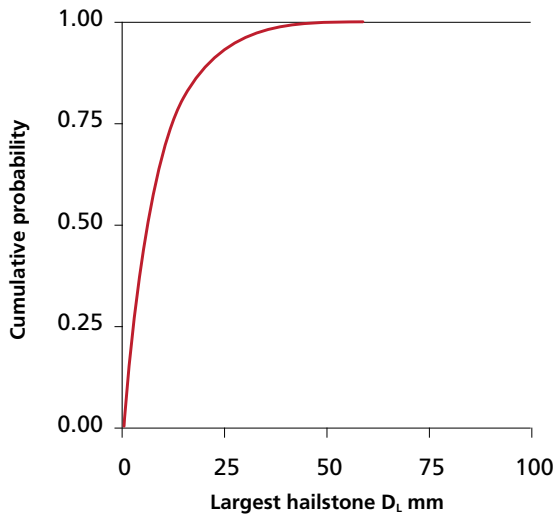
$$b_{D_L} = 6.55$$

$$\begin{aligned} F_{D_L}(d_L) &= 1 - \frac{n_{obs}(d_L)}{n_{obs}(0)} \\ &= 1 - \frac{\exp(m_{D_L} \cdot d_L + b_{D_L})}{\exp(b_{D_L})} \end{aligned} \quad (9)$$

$$f_{D_L}(d_L) = -\frac{m_{D_L}}{\exp(b_{D_L})} (\exp(m_{D_L} \cdot x + b_{D_L})) \quad (10)$$

$$d_L(p) = -\frac{\ln(1-p)}{m_{D_L}} \quad 0 \leq p < 1 \quad (11)$$

**Figure 8.** Cumulative distribution function of equivalent diameter of largest hailstone  $D_L$  implied by Grieser and Hill (2019)





Let us estimate  $D_A$ , the equivalent diameter of the average hailstone in mm, as a function of  $D_L$ , equation (12), as suggested by Grieser and Hill (2019).

$$D_A = a_{D_A} D_L^{b_{D_A}} \text{ mm} \quad \hat{a}_{D_A} = 1.449 \quad \hat{b}_{D_A} = 0.649 \quad (12)$$

Using Wong et al. (1987)'s estimate of  $\alpha = 1.75$  and rearranging equation (1), one can estimate the  $\beta$  term for gamma-distributed hailstone diameter as shown in equation (13), and estimate the cumulative distribution function of the hailstone diameter  $d$ , as shown in equation (14). The fraction of hailstones between diameters  $a$  and  $b$  is then given by equation (15).

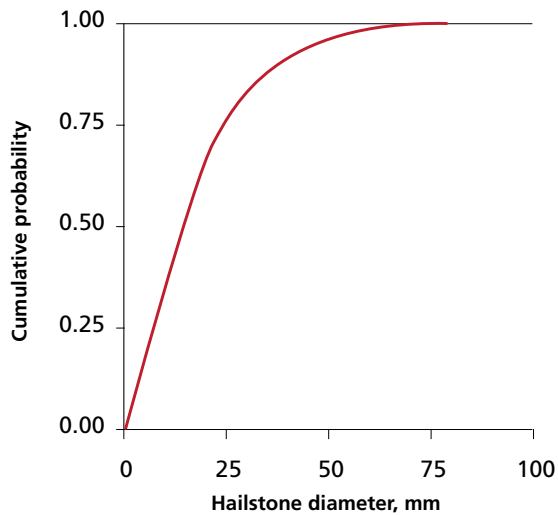
$$\beta = \frac{\alpha}{D_A} \quad \alpha \approx 1.75 \quad (13)$$

$$F_D(d) = \int_0^d \frac{\beta^\alpha x^{\alpha-1} \exp(-\beta x)}{\Gamma(\alpha)} dx \quad (14)$$

$$F_{ab} = \int_{x=a}^b \frac{\beta^\alpha x^{\alpha-1} \exp(-\beta x)}{\Gamma(\alpha)} dx \quad (15)$$

For example, given  $D_L = 50$  mm,  $D_A \approx 18$  mm, and the cumulative distribution function for equivalent hailstone diameter is illustrated in Figure 9. Note the gamma distribution is unbounded above, not at  $D_L = 50$  mm, but the distribution it is merely intended as an approximation, not as a mathematical rule.

**Figure 9.** Cumulative distribution function of hailstone diameter with average = 18 mm and alpha = 1.75



To estimate number of hailstones per square metre, let us use the product of Grieser and Hill's (2019) estimates of hit rate and duration, shown in equations (16) and (17), multiplied to get number of hailstones per square metre over the duration of the storm equation (18). Note that Grieser and Hill's (2019) tabulated functions and parameter values for duration and hitrate do not seem to match their figures for duration. In Table 4, duration is linear with  $D_L$ , but their figure for shows a power function. When one inputs their parameters for a linear function in the power function of equation (17), the result almost matches their figure. The present author rederived the duration from their chart, producing the parameter values shown here. The number of hailstones with diameters between  $a$  and  $b$  striking an area  $A$  is given by equation (19).

$$Hr = a_{Hr} D_L^{b_{Hr}} \text{ min}^{-1} \text{ m}^{-2}$$

$$\hat{a}_{Hr} = 11980 \quad (16)$$

$$\hat{b}_{Hr} = 1.237$$

$$T = a_T D_L^{b_T} \text{ min} \quad \hat{a}_T = 5.9264 \quad \hat{b}_T = 0.2652 \quad (17)$$

$$N = Hr \cdot T \text{ m}^{-2} \quad (18)$$

$$= a_{Hr} D_L^{b_{Hr}} \cdot (a_T D_L^{b_T})$$

$$N_{ab} = N \cdot A \cdot f_{ab} \quad (19)$$

$$= a_{Hr} D_L^{b_{Hr}} \cdot (a_T D_L^{b_T}) \cdot A \cdot f_{ab}$$

If we only know a building's geographic location and the projected area  $A$  of the surface, we can use Etkin (2018) to estimate frequency of hailstorms and equations (9) through (19) to estimate the number and size distribution of hailstones conditioned on the occurrence of a hailstorm and a non-exceedance probability  $p$  for the largest hailstone from equation (11).

If we know that a hailstorm has occurred at a location, the maximum hailstone size  $D_L$  at that location, and the vertical projection of area of some surface such as a roof, we can use equations (12) through (19) to estimate the number and size distribution of hailstones striking the surface. That is, the hitrate, duration, and distribution of hailstone diameters are all modeled here as deterministic functions a single random variable  $D_L$ . For a shingle of 0.16 m<sup>2</sup>, one can estimate the number and size distributions of hailstones as a function of  $D_L$ .

### **3.4 Damage analysis**

#### **3.4.1 Limit states of interest**

Recall that in performance-based engineering, one inputs a demand parameter to a fragility function to estimate the probability that damage to some component reaches or exceeds a prescribed limit state. In the present case, we want to estimate the probability that a hailstone of diameter  $D$  will cause a shingle to exceed a limit state of interest, that is, causing an undesirable physical change in the shingle, discussed next.

What constitutes an undesirable physical change to the shingle? From a homeowner's perspective – which is the one that matters most in a performance-based framework – shingle failure seems to constitute either cosmetic failure or functional failure. Cosmetic failure seems to occur either if enough granules are dislodged at the point of impact to be visible to a roof inspector standing on the roof and clearly identifiable as a hailstone hit, or the shingle suffers a permanent deformation – a shallow pit where the hailstone struck – that is visible to the roof inspector. Functional failure means tearing of the shingle, that is, a crack or tear that would breach its moisture barrier and allow water damage to roofing. Deformation of the shingle so that water sheds laterally rather than down-slope would constitute both a cosmetic and a functional failure.

Several authors reviewed earlier suggest that diminution of the life of the shingle also constitutes failure, but none seem actually to quantifiably define the life of a shingle. Some suggest that dislodged granules reduce shingle life by exposing the asphalt to ultraviolet light, but Marshall et al. (2004) found otherwise. So let us continue to define failure solely by cosmetic damage or breach of the moisture barrier.

Neither of the standard impact rating tests have the user measure or otherwise characterize cosmetic damage. However, Haag Engineering (2006) equates damage that dislodges granules, exposes the coating bitumen, and generates a detectable bruise. For that reason, let us equate the capacity of a shingle to resist cosmetic damage with the capacity of the shingle to resist breaching of the moisture barrier. That is, the two limit states are taken to be coincident: a hailstone that breaches the moisture barrier also causes cosmetic failure and vice versa.

Note that the Haag et al. (2020) tests are interesting, but seem uninformative about either limit state. They are silent about whether the shingles continue to provide a moisture barrier or whether they suffer cosmetic damage. It is unclear how damage to the fiberglass constitutes a limit state that matters.

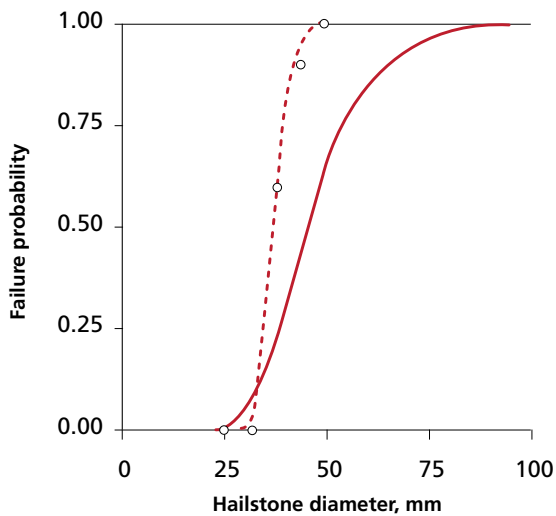
#### **3.4.2 Fragility of non-impact-resistant shingles**

Can one use the Marshall et al. (2002) tests to create a fragility function for impact-resistant shingles? While the tests tell us about the damageability of the shingles they tested, they are silent on the effect of impact resistance class (in the sense of UL 2218 or FM 4473) on fragility. For present purposes, let us assume therefore that none of the shingles the authors tested had a UL or FM impact rating. Recall that the limit state included “punctures, tears, or fractures (bruises) in the shingle mats as well as the displacement of granules to visibly expose the underlying bitumen,” which seems consistent with our limit state. Let us use method B of Porter et al. (2007) to estimate the parameter values of a cumulative distribution function to approximate the fragility of non-rated shingles.

In method B, one knows the fraction of specimens that failed when exposed to some bounding (B) level of demand. The circles in Figure 10 represent the failure data for laminated shingles, the most common type. One fits a curve to the data (the dashed line), such as in the form of equation (20), in which  $x$  is the demand parameter (here, hailstone diameter),  $\theta$  and  $\beta$  are parameters of the distribution,  $\Phi$  denotes the standard normal cumulative distribution function evaluated at the term in parentheses, and  $P_f(x)$  denotes the probability that a specimen of the component type of interest will reach or exceed the limit state observed in the test. The parameter  $\theta$  denotes the median capacity of the component to resist the limit state of interest (i.e., the level of demand  $x$  that will cause 50% of specimens to fail) and  $\beta$  measures variability in capacity, referred to here as the logarithmic standard deviation of capacity.

$$P_f(x) = \Phi\left(\frac{\ln(x/\theta)}{\beta}\right) \quad (20)$$

**Figure 10.** Fragility of non-impact-resistant laminated shingles as implied by Marshall et al. (2002) tests.



The shingle tests show low variability in capacity: the fragility function is very steep. Here, capacity refers to the maximum diameter of ice ball that the shingle can resist without reaching or exceeding the limit state. When one fits a lognormal cumulative distribution function to the first three rows of Table 2, the best-fit standard deviation of the natural logarithm of capacity tends to be small: 0.07 for fiberglass shingles, 0.22 for organic, and 0.09 for 30-year laminated shingles. The low variability seems to reflect the highly uniform manufacture of the shingles and particularly of the highly uniform testing regimen. Nature would add greatly to this variability through highly variable hailstone material properties, shape, attack angle, and terminal velocity. Greater variability in these attributes would tend to make the fragility function more uncertain, which would make it appear wider or flatter.

Method B offers a test of uncertainty and a standard remedy when it appears to be too low. Both the test regimen (only frozen tap water ice balls and only normal impact), and the very low uncertainty in the dashed curve ( $\beta = 0.07$ ), suggest that the dashed line in Figure 10 is too steep, that the uncertainty is too low. Appendix H.1.1 of FEMA P-58 (Applied Technology Council 2012) offers a method to increase the logarithmic standard deviation of capacity to account for real-world variability. One calculates a larger  $\beta$  by means that will not be detailed here, selects a point on the original fragility function to preserve on the revised fragility function to reduce the chance of biasing the annualized failure rate, finds the value of demand  $x_p$  associated with that failure probability, and rotates the fragility function about that point ( $x_p, p$ ) to find a new median capacity that passes through the original curve at that point but has the larger, more realistic value of  $\beta$ . The solid line in Figure 10 represents the revised fragility function following the FEMA P-58 procedures: it has  $\theta = 46$  mm and  $\beta = 0.25$ .

### 3.4.3 Fragility of impact-resistant shingles

The studies discussed here generally agree that loss of the moisture barrier constitutes a failure. Failure under UL 2218, FM 4473, or the IBHS (2019) breach severity 1, 2, or 3 all seem to equate with functional failure. To construct a fragility function for this limit state, I propose to use method C of Porter et al. (2007). Method C refers to the case where one has observational data about specimens that were subjected to known levels of excitation, and none of the specimens failed. The component is said to be capable (the C in method C) of resisting this level of demand without failing. Porter et al. (2007) consider several method-C situations, in one of which none of the specimens experienced any apparent distress. In that situation, one chooses a logarithmic standard deviation of capacity (Porter et al. 2007 suggest  $\beta = 0.4$ ). One then assigns the highest value of demand in the data set (denoted by  $r_{max}$ ) to a low failure probability denoted by  $F$  (0.01 for a large number of specimens). These two values provide enough information to drive a lognormal cumulative distribution function through the point ( $r_{max}, F$ ) and calculate the median capacity  $\theta$ , by equation (21), with results shown in Table 3. The table also includes the fragility of non-impact-resistant shingles, for convenience. In the equation,  $\Phi^{-1}$  denotes the inverse of the standard normal cumulative distribution function evaluated at the value in parentheses.

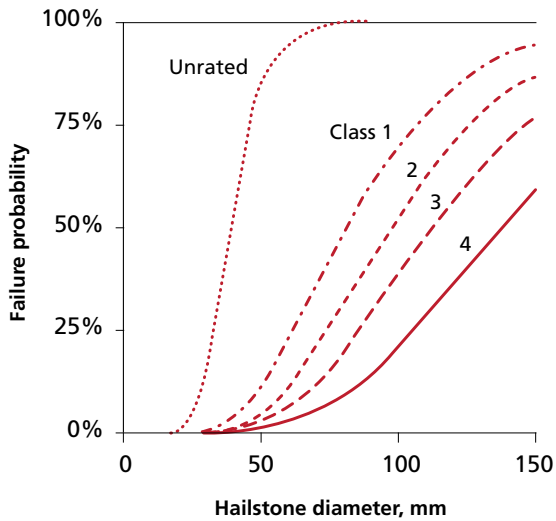
$$\theta = r_{max} \exp(-\Phi^{-1}(F) \cdot \beta) \quad (21)$$

**Table 3. Shingle fragility for breaching moisture barrier.**

| UL 2218 or FM 4473 class | $r_{max}$ , mm | $\exp(-\Phi^{-1}(F) \cdot \beta)$ | $\theta$ , mm | $\beta$ |
|--------------------------|----------------|-----------------------------------|---------------|---------|
| None                     |                |                                   | 39            | 0.25    |
| 1                        | 32             | 2.54                              | 81            | 0.4     |
| 2                        | 38             | 2.54                              | 97            | 0.4     |
| 3                        | 44             | 2.54                              | 112           | 0.4     |
| 4                        | 51             | 2.54                              | 137           | 0.4     |

Then equation (20) gives the shingle's fragility function, where  $x$  denotes the equivalent diameter of a single hailstone striking the shingle. Figure 11 illustrates the fragility functions for impact-resistant laminated shingles, and repeats the fragility function for unrated shingles for comparison.

**Figure 11.** *Fragility of asphalt shingles to the strike of a single hailstone.*



Are the fragility functions for impact-resistant shingles too low? That is, do these fragility functions overestimate the capacity of impact-resistant shingles to resist hailstone strikes? Maybe not, for three reasons: angle of attack, hailstone density, and crushing energy.

1. First UL 2218 and FM 4473 both have the projectile impact the shingle at a 90-degree angle, which is rare. Hailstones that impact at more common, lower angles of attack will tend to transfer less kinetic energy to the shingle and cause less damage. The April 28, 2021, hailstorm in Norman, Oklahoma produced as heavy damage to the vertical sides of vehicles as it did their roofs, suggesting angles of attack near 45 degrees, which would transfer at most about 70% of their kinetic energy to out-of-plane deformation of the impacted surface.
2. Second, as IBHS (2019) and Brown-Giammanco et al. (2021) point out, perfectly spherical steel balls and maximum-density ice spheres tend to represent a worst-case approximation of real hailstones, which can have much lower densities and thus lower terminal velocities.
3. Third, real hailstones are more likely to fracture on impact than are ice spheres. Steel balls never fracture on impact. The fracture transfers kinetic energy to the mechanical energy required to break bonds between water molecules, leaving less transferred to the shingle. Crushing ice requires about 3000 J/kg (Kim and Gagnon 2016), so to crush a 51-mm sphere of ice can absorb up to 187J, many times its kinetic energy in freefall (32J according to UL 2218). Of course, hailstones fracture on impact rather than being completely crushed, but the point remains that much of the kinetic energy of real hailstones can be absorbed by crushing rather than transferring to the roofing tile, and that is less likely to occur in ice spheres and impossible in steel.

### 3.4.4 Have we ignored important fragility data?

Why not use the breach-severity part of the IBHS (2019) test protocol to inform a fragility function about breaching the moisture barrier? It is unclear on what basis the experts judge breach severity. "Expert judgment" seems to mean that an expert estimates a clearly defined quantity without the aid of measurement or calculation. But the IBHS breach severity has no measurement or calculation that the expert is estimating. It is unclear what a breach of severity 0 means: the absence of a breach or a breach that is in some sense small? It seems clear that any breach of severity 1, 2, or 3 would indicate a nonzero (and presumably detectable and measurable) breach of the moisture barrier, but how much is too much? Our criterion is binary: no breach or a breach. Should the threshold be 1, 2, or 3, and why? Answering that question could make the IBHS test relevant to the present purpose.

Why not use the IBHS (2019) test's granule-loss and dent-volume tests to measure cosmetic damage? The measures seem too hard to apply here. One cannot expect to see the loss of a single granule from the street or even standing on the roof. The loss of many granules over a small area would matter at some point, but the test is silent about the degree at which one can reliably see the loss of granules. Measures of dent volume also seem relevant, but IBHS relies on instruments rather than visual appearance to measure dent volume, and does not explicitly relate dent volume to its impact on appearance. Can one reliably see a dent with 11 mm<sup>3</sup> volume? The authors make no statement on the point. Answering these questions could make the IBHS test more relevant for present purposes.

Have we accounted for the effect of age on shingle fragility? The fragility function for unrated shingles account for aging because it is based on testing of 11-year-old shingles. The author was unable to find the necessary data to determine how and the degree to which shingle age affects the fragility of impact-resistant shingles, and in any case the nature of method-C fragility functions for impact-resistant shingles may already cause an overestimate of damageability.

### 3.4.5 Simplifying the damage analysis with $D_L$ as the demand parameter

To use the fragility functions shown in Table 3 and Figure 11, one would have to estimate the number and size of every hailstone striking every shingle. That is probably practical, but unnecessary. Recall that hitrate, storm duration, and the distribution of hailstone diameters are all given as deterministic functions of the equivalent diameter of the storm's largest hailstone,  $D_L$ . Which suggests that given the exposed area of a shingle, one can calculate shingle fragility as a function of  $D_L$ , accounting for all the hailstones that strike the shingle, even if none of them approach  $D_L$  in size.

Equation (19) tells us how many hailstones of diameters  $a$  to  $b$  strike an area as a function of  $D_L$ . The exposed area of a shingle  $A_s = 0.165 \text{ m}^2$ . One can use equation (20) with the theorem of total probability to integrate over hailstone diameter. See equation (22). In the equation,  $D_L$  is the uncertain equivalent diameter of the largest hailstone,  $d_L$  is a particular value of it, and  $P_{fL}(d_L)$  denotes the failure probability of a shingle in a storm whose maximum hailstone diameter is  $d_L$ .  $P_{fL}$  also expresses the expected fraction of shingles on a roof that would have to be replaced if one only replaced damaged shingles.

$$\begin{aligned}
 P_{fL}(d_L) &= 1 - \prod_{x=1}^{x_U} \left( 1 - \Phi \left( \frac{\ln(x/\theta)}{\beta} \right) \right)^{N_{ab}} \quad x \in \{5, 6, 7, \dots, x_U\} \quad (22) \\
 a &= x - 0.5 \\
 b &= x + 0.5 \\
 &\approx \Phi \left( \frac{\ln(d_L/\theta_L)}{\beta_L} \right)
 \end{aligned}$$

Note that some contractors commonly recommend replacing a roof when the fraction of damaged shingles exceeds some threshold value  $E$  such as  $E = 0.5$ , in which case equation (22) becomes

$$P_{fL}(d_L) = \begin{cases} \Phi\left(\frac{\ln(d_L/\theta_L)}{\beta_L}\right) & \Phi\left(\frac{\ln(d_L/\theta_L)}{\beta_L}\right) < E \\ 1 & \Phi\left(\frac{\ln(d_L/\theta_L)}{\beta_L}\right) \geq E \end{cases} \quad (23)$$

Figure 12 shows the results of evaluating equation (22) up to  $x_u = 150$ . Unsurprisingly, the curves are also approximately lognormal: the product of large numbers of random variables tends to approach the lognormal distribution. One can use a new set of fragility functions, these where the demand parameter is  $D_L$  and accounts for the number and size distributions of all hailstones striking a shingle, rather than the demand parameter being the diameter of a single hailstone striking it.

**Figure 12.** Shingle failure probability as a function of the storm's largest hailstone.

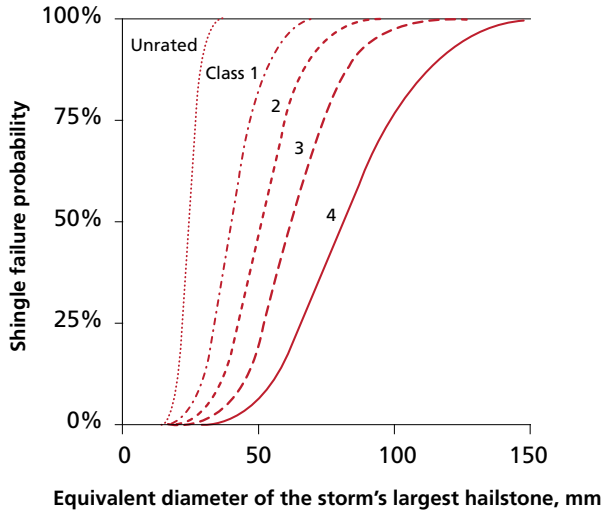


Table 4 presents the parameters of this second set of fragility functions, denoted here by  $\theta_L$  and  $\beta_L$ . Note that failure probabilities in terms of  $D_L$  are much higher than those in terms of the diameter of a single hailstone. That is unsurprising, even though the largest hailstone is unlikely to strike a given shingle. The reason is that the fragility functions shown in Figure 12 accounts for the hundreds of hailstones that can strike a shingle during the duration of a storm. The chance of at least one low-probability failure in many trials can be larger than the chance of a single high-probability failure in a single trial. Note also that  $\theta_L$  and  $\beta_L$  are revised to have a larger, more credible, uncertainty value  $\beta_L = 0.25$ . The revised curve passes through the same point of  $(d_L, 0.1)$  as the original curve.



For a sense of the storm that will leave an impact-resistant roof undamaged, the table also shows the value of  $D_L$  associated with some very small fraction of roof damage, say  $f_0 = 1\%$  damage, using equation (24) with  $f_0 = 0.01$ . It also shows the chance that any given hailstorm will produce a larger  $D_L$ , using equation (25). The table shows that an estimated 12% of hailstorms damage unrated roofs, and that class-4 roofs avoid damage in all but about 0.8% of hailstorms, i.e., 1 in 125.

$$d_L(f_0) = \theta_L \cdot \exp(\beta_L \cdot \Phi^{-1}(f_0)) \quad (24)$$

$$P[D_L > d_L(f_0)] = 1 - F_{D_L}(d_L(f_0)) \quad (25)$$

$$= \frac{\exp(m_{D_L} \cdot d_L(f_0) + b_{D_L})}{\exp(b_{D_L})}$$

**Table 4. Shingle fragility in terms of the equivalent diameter of the storm's largest hailstone,  $D_L$ .**

| UL 2218 or FM 4473 class | $\theta_L$ , mm | $\beta_L$ | $D_L$ with $\leq 1\%$ damage, mm | Probability of over 1% damage |
|--------------------------|-----------------|-----------|----------------------------------|-------------------------------|
| Unrated                  | 29              | 0.25      | 19                               | 12%                           |
| 1                        | 41              | 0.23      | 24                               | 7%                            |
| 2                        | 52              | 0.24      | 29                               | 4%                            |
| 3                        | 63              | 0.25      | 35                               | 2%                            |
| 4                        | 82              | 0.27      | 44                               | 0.8%                          |

### 3.5 Loss analysis

#### 3.5.1 Repair cost as a function of damage

Let us model repair cost as suggested by Marshall and Herzog (1999). Equation (26) adapts their methodology using the quantities calculated in the damage analysis. In the equation,  $L(d_L)$  denotes the hail-damaged roof loss to a building in a hailstorm whose largest hailstone has an equivalent diameter of  $d_L$ . Loss is measured here solely by the cost to repair hail damaged roofing. (One might also try to include the inconvenience and stress involved in roof repairs, the environmental harm caused by the debris, and on the plus side the jobs created, spur to economic activity, and perhaps others.)  $P_{f_2}$  is the fraction of roofing shingles requiring replacement from equation (22),  $U$  is the unit repair cost (material, waste, labour, overhead, profit, and tax per unit area,  $A$  is area of the roof in the same units (e.g., number of squares),  $R$  is a factor to account for repair difficulty, which for the average case is taken here as 1.0.

$$L(d_L) = P_{f_L}(d_L) \cdot U \cdot A \cdot R \quad (26)$$

Let us replace  $U \cdot A \cdot R$  with  $V$ , to denote the replacement cost new of the whole roof. Let us also acknowledge that when the fraction of shingles damaged exceeds some threshold, one replaces the whole roof. Then equation (26) becomes equation (27):

$$\begin{aligned} L(d_L) &= P_{f_L}(d_L) \cdot V & P_{f_L}(d_L) < E \\ &= V & P_{f_L}(d_L) \geq E \end{aligned} \quad (27)$$

### 3.5.2 Long-term average annualized loss

Let us now estimate the average annual hail loss to an asphalt shingle roof of a given level of impact resistance, surface area, and geographic location. Equation (28) gives the expected annualized loss associated with hail damage to asphalt shingle roofs, in year  $y$  (so that we can later account for climate change). The integrand has these parts: loss given a hailstorm with equivalent diameter of the largest hailstone  $d_L$  from equation (27), frequency of hailstorms in year  $y$ , e.g., from Etkin (2018), and probability density of storms with equivalent diameter of the largest hailstone  $d_L$  from equation (10).

$$EAL(y) = \int_{d_L=5}^{\infty} L(d_L) \cdot f_h(y) \cdot f_{D_L}(d_L) \cdot dd_L \quad (28)$$

Removing constants from the integrand and assuming stationary hazard over the life of the roof, equation (28) becomes equation (29). In the equation,  $m_{D_L} = -0.111 \text{ mm}^{-1}$ ,  $b_{D_L} = 6.55$ ,  $\theta_L$  and  $\beta_L$  are given by Table 4 and  $F_L$  denotes expected value of the fraction of the roof that needs to be replaced given that a hailstorm occurs. In equation (30), the expression for  $F_L$ , the denominator normalizes the probability density function  $f_{D_L}(d_L)$  to integrate to 1.0 for  $D_L \geq 5$  mm, based on the assumption that Etkin (2018) only counts the frequency of hailstorms with  $D_L \geq 5$  mm. The denominator is necessary because the expression for  $f_{D_L}(d_L)$  counts  $0 < D_L < 5$  mm, as shown in Figure 9.

$$EAL = f_h(t=0) \cdot V \cdot F_L \quad (29)$$

$$F_L = \frac{\int_{d_L=5}^{\infty} L(d_L) \cdot f_{D_L}(d_L) \cdot dd_L}{1 - F_{D_L}(d_L = 5)} \quad (30)$$

Equation (30) only depends on parameters of hail-resistance rating and on the probability density function for  $D_L$ , which we have taken to be independent of location, time, or other variables considered here, and so can be evaluated for each hail rating level. See Table 5 for results. It says for example that the average hailstorm causes 9.7% loss to unrated roofs, accounting for the chance of various hailstone sizes and hitrates, including hailstorms that cause no damage or complete loss, and anything in between.

**Table 5.** Expected fraction of roof value lost given a hailstorm, by hail rating,  $F_L$ .

| Unrated | 1     | 2     | 3      | 4      |
|---------|-------|-------|--------|--------|
| 0.097   | 0.030 | 0.011 | 0.0047 | 0.0011 |

### 3.5.3 Frequency-severity formulation of loss

Insurance actuaries commonly think about disaster losses in terms of the frequency with which a claim occurs and the severity of the loss if it occurs.

Equation (31) estimates the claim frequency  $f_{claim}$  in year  $y$  given hail rating  $c$ , as the frequency with which hailstorms occur,  $f_h(y)$ , for example from Etkin (2018), times the fraction of storms that would cause a class- $c$  roof to experience more than a very small fraction of roof damage, as suggested by equation (25) and Table 4.

$$f_{claim}(y, c) = f_h(y) \cdot P[D_L > d_L(f_0)] \quad (31)$$

The average claim severity is given by equation (32), by the theorem of total probability.

$$\begin{aligned} s_{claim}(y, c) &= \int_{d_L=d_L(f_0)}^{\infty} L(d_L) \cdot f_{D_L}(d_L) \cdot dd_L \\ &= \frac{EAL(y)}{f_{claim}(y, c)} \end{aligned} \quad (32)$$

## 3.6 Benefit-cost analysis

### 3.6.1 Benefit-cost ratio

The present value of future hail loss is given by equation (33), in which  $r$  is a discount rate to reflect the time value of money and  $\tau$  is a planning period over which one recognizes the future losses for the roof.

The benefit of initially installing an impact-resistant roof rather than a non-impact-resistant roof is given by equation (34), in which the subscript 0 denotes non-impact-resistant roofing and  $c$  denotes a UL 2218 or FM 4473 class. Equation (35) gives the incremental cost of initially installing a class- $c$  roof rather than an unrated roof, and equation (36) gives the benefit-cost ratio. Note that the difference in cost in equation (35) is exclusively the difference in the material cost of the shingles, since the labour is the same.

$$PV = EAL \frac{1 - \exp(-r\tau)}{r} \quad (33)$$

$$\begin{aligned} B &= PV_0 - PV_c \\ &= (EAL_0 - EAL_c) \frac{1 - \exp(-r\tau)}{r} \end{aligned} \quad (34)$$

$$C = (U_c - U_0) \cdot A \cdot R \quad (35)$$

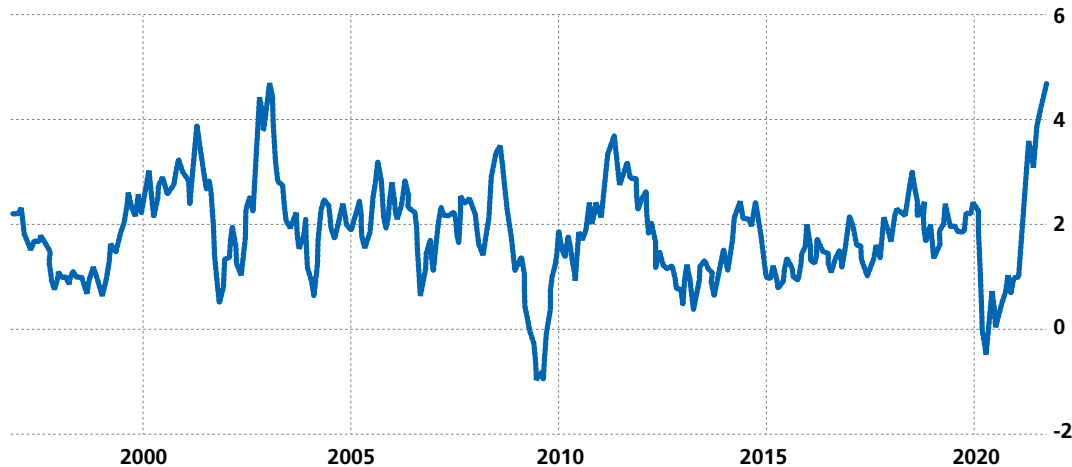
$$BCR = \frac{B}{C} \quad (36)$$

The discount rate  $r$  and planning period  $\tau$  will depend on who is buying the roof and under what situation.

### 3.6.2 Insurer's decision situations

An insurer paying a hail claim will use investment capital, suggesting a real discount rate of the long-term average return on real estate (in Canada, about 8.5%, per McLean 2021), less a long-term average inflation rate (e.g., 2% in Canada; Figure 13, for a discount rate of  $r = 6.5\%$ ).

Figure 13. Canada inflation rate (Trading Economics 2021).



Every year, most insured homeowners renew their policies, but some do not. For example, some homeowners will sell their house next year to a new owner who contracts with a different insurer. Which means that farther into the future, all else being equal, the current insurer has a decreasing likelihood of enjoying benefits from an improved roof. One can model that process and estimate the fraction of the total avoided future losses that the first and all subsequent insurers enjoy.

Let  $R$  denote the annual retention rate, that is, the ratio of the number of retained customers to the number at risk. Here, that means the chance that the present insurer will insure a given homeowner for the same house next year. For purposes of estimating the benefits that the present insurer will enjoy from an improved roof, let us conservatively ignore the chance that the present insurer will contract with a different policyholder for the same property.

In the following,  $P(t)$  denotes the chance that the present insurer insures the given property in year  $t$ . It is given by equation (37).  $EAL_0$  and  $EAL_c$  denote the expected annualized repair costs under as-is and what-if conditions, respectively.  $B(t)$  denotes the present value of the loss avoided (the benefit) in year  $t$ . It is given by equation (38), in which  $r$  denotes the discount rate. Let  $\tau$  denote the useful life of the roof.  $B$  denotes the present value of all avoided future losses, again from equation (34).  $B'$  denotes the expected present value of all avoided future losses enjoyed by the present insurer, from equation (39).

$$P(t) = R^t \quad (37)$$

$$B(t) = R^t (EAL_0 - EAL_c) \cdot \exp(-rt) \quad (38)$$

$$\begin{aligned} B' &= \sum_{t=0}^{\tau-1} P(t)B(t) \\ &= \sum_{t=0}^{\tau-1} R^t (EAL_0 - EAL_c) \cdot \exp(-rt) \end{aligned} \quad (39)$$

It is interesting to know what fraction of the total benefits are enjoyed by the first insurer, which is given by equation (40). Note that the ratio is a function of just the discount rate, retention rate, and life of the roof.

$$\begin{aligned} \frac{B'}{B} &= \frac{\sum_{t=0}^{\tau-1} R^t (EAL_0 - EAL_c) \cdot \exp(-rt)}{(EAL_0 - EAL_c) \frac{(1 - \exp(-r\tau))}{r}} \\ &= \sum_{t=0}^{\tau-1} \frac{R^t \cdot \exp(-rt)}{(1 - \exp(-rt))} \end{aligned} \quad (40)$$

It turns out that for realistic parameter values, namely  $R = 0.9$ ,  $r = 6.5\%$ , and  $\tau = 20$  years, equation (39) yields about the same results as equation (34) if the insurer received all the benefits for the first 8 years. Some insurers reduce claim payments for older roofs to account for depreciation. That wrinkle is omitted here.

### 3.6.3 Buyers who do not expect to recoup the higher price of the roof

Let us next consider buyers of a new home whose developer passes on the cost of the higher-price roof. Those buyers pay with a mortgage. For that situation, a reasonable discount rate is the real cost of borrowing: a long-term average 5-year fixed closed rate (about 3% in late 2021, TD Canada Trust 2021), less a long-term average inflation rate (e.g., 2%, per Trading Economics 2021), i.e.,  $r = 1\%$ . Let us take their planning period as the average tenure of  $\tau = 10$  years. Older homeowners might stay in their homes longer. Some might have a planning period closer to the life of the roof,  $\tau = 20$  years. For a conservatively high cost and low benefit-cost ratio, let us consider the home buyer who does not expect to recoup the higher price of the roof at the time of resale.

Later owners have a similar decision situation. In late 2021, several home sellers in Calgary emphasize impact-resistant roofing among the features of the house, which suggests that impact-resistant roofing is a market feature with an associated value. One could perform a hedonic price analysis to estimate the value like those of Simmons et al. (2002), Simmons and Sutter (2007), Awondo et al. (2016, 2019) or Porter et al. (in press). Absent such an analysis, one could assume that the buyer pays 100% of the cost of the hail-resistant roof, the same cost of borrowing ( $r = 1\%$ ), and can expect the same  $\tau = 10$  years of benefit.

#### **3.6.4 Societal viewpoint**

From a societal viewpoint, it makes sense to consider the entire life of the roof, perhaps 20 years for laminated architectural shingles with other qualities similar to impact-resistant products. Regarding the discount rate, the Treasury Board of Canada Secretariat (2007 pg. 38) suggests using a social time-preference rate of 3% where consumer consumption is involved and there are no or minimal resources involving opportunity costs.

## 4. Findings

Let us now apply the foregoing methodology to estimate the costs and benefits of impact-resistant asphalt shingle roof cover for a particular house design.

### 4.1 Sample building and locations

Let us consider the roof of an average-size house, that is, using the average roof area of a statistical sample of 102 single-family dwellings in Canada (Porter et al. 2021): about 167 m<sup>2</sup> (1,800 ft<sup>2</sup>). The typical newer house from this sample of 102 houses has a roof pitch of approximately 4:12 to 6:12. Let us place the hypothetical house in Calgary Alberta at 51.159N, -114.158E, near the Sherwood neighborhood in north Calgary. To install a roof with a 10% buffer for waste would require 20 roof squares ( $A = 20$  squares). It will also be useful later to consider two addition locations: one where the hailstorms occur one time per year, and another at the location where the hail hazard is greatest. The table shows the number of hail days per year at each location. See Table 6.

**Table 6.** *Sample building and locations.*

| Location                        | Longitude degrees E | Latitude degrees N | Frequency |
|---------------------------------|---------------------|--------------------|-----------|
| 30 km east of Calgary, AB       | -113.300            | 51.110             | 1.00      |
| Calgary, AB                     | -114.158            | 51.159             | 2.35      |
| 100 km northwest of Calgary, AB | -115.200            | 51.900             | 5.71      |

### 4.2 Marginal cost and replacement cost

As shown in Table 1, class-4 shingles could add as little as \$59 per square (CertainTeed Landmark IR, \$155 per square, versus BP Canada Dakota, \$96 per square) or as much as \$244 per square (Tamko Stormfighter IR, \$340 per square), suggesting a midrange marginal cost of about \$164 per square (TruDefinition Weatherguard HP, \$260 per square). All these figures are pre-tax, which would add 5% in Alberta.

Thus, the minimum marginal cost for a 20-square roof is  $C = \$300$  (class 3) to \$1,600 (class 4, both after-tax 2021 CAD). The mid-range marginal cost at \$164 per square totals  $C = \$3,400$  after GST, about equal to Calgary's \$3,000 rebate. The most-expensive class-4 shingles cost \$340 per square, adding \$5,100 to the roof replacement cost after tax.

The unrated roof replacement cost at \$251/square is  $V = \$5,300$  including demolition of the old roof, underlayment (which contributes about 10% of the total where it is used), installation of the new roofing, and GST. A class-4 roof has a replacement cost of \$8,700, subject to variability based on repair difficulty and other factors.

Costs can vary geographically and over time. They are not presented here as universal for all locations and over time.

### 4.3 Hazard and fragility

Etkin (2018) estimates Calgary hail frequency of  $f_h(0) = 2.35$  days per year for 2007. We lack sufficient information to estimate the change in hailstorm frequency or severity, so for present purposes we hold hazard stationary. Other hazard parameters – storm duration, hitrate, and hailstone size distribution – are not modeled here as geographically varying, and are taken from Grieser and Hill (2019) as discussed earlier. We calculate the hailstone size distribution using the simple gamma distribution, and shift it by normalizing its probability density function by its integral from 5 mm to infinity. Fragility is taken as described in section 3.4.

### 4.4 Loss analysis

Table 7 presents an estimate of roof repair costs, that is, contributors to the unit repair cost  $U$ , as of this writing, in Calgary. It shows that labour accounts for approximately 60% of the total unit cost for unrated shingles, and about 40% for class-4 impact-rated shingles.

**Table 7.** Contributors to repair cost per roofing square.

| Cost parameter                       | Unrated  | Class 4  | Comment  |
|--------------------------------------|----------|----------|--|
| Underlayment demo + replace material | \$6.69   | \$6.69   | Unit cost roof underlayment, demolish & replace 15# felt, from RSMMeans (2020) pg. 73                  |
| Underlayment demo + replace labour   | \$22.20  | \$22.20  | Ditto  |
| Shingle demo & install labour        | \$125.73 | \$125.73 | Labour unit cost demolish & install 30-year comp shingles RSMMeans (2020, pg. 73)                      |
| Shingle material low                 | \$85.00  | \$167.00 | Marquis Weathermax (Home Depot Calgary); Mystique (RONA); TruDefinition Duration (Menards, Home Depot) |
| Shingle material moderate            | \$96.00  | \$260.00 | Dakota (RONA.ca); Manoir (RONA.ca); TruDefinition Weathguard HP (Hanscomb Ltd 2020)                    |
| Shingle material high                | \$99.00  | \$340.00 | Everest (RONA.ca); Vista AR (Hanscomb Ltd 2020); Stormfighter IR (Hanscomb Ltd 2020)                   |
| Total cost/sq low                    | \$239.62 | \$321.62 |  |
| Total cost/sq moderate               | \$250.62 | \$414.62 |  |
| Total cost/sq high                   | \$253.62 | \$494.62 |  |
| Marginal cost/sq low                 | \$0.00   | \$82.00  |  |
| Marginal cost/sq moderate            | \$0.00   | \$164.00 |  |
| Marginal cost/sq high                | \$0.00   | \$241.00 |  |
| Labour as % of total low             | 62%      | 46%      |  |
| Labour as % of total moderate        | 59%      | 36%      |  |
| Labour as % of total high            | 58%      | 30%      |  |



## 4.5 Frequency, severity, benefit, cost, and benefit-cost ratio

### 4.5.1 Results

Table 8 presents claim frequency (labeled Freq) and claim severity (labeled Severity), expected annualized loss (EAL, 2021 CAD \$/year), present value of loss (PV, 2021 CAD), benefit relative to unrated shingles (2021 CAD), and benefit-cost ratio (unitless) for a variety of decision situations. Note that claim frequency is different from hailstorm frequency, because only some hailstorms cause a claim. Figures in the table are rounded to reduce the appearance of excessive accuracy, although the calculations were carried out to greater precision.

The table is organized around a base case from society's perspective: a 20-square roof that adds \$3,400 to its replacement cost, but saves a long-run average of \$10,000 in avoided future repair costs over a 20-year life of the roof. The discount rate for the base case reflects the Treasury Board of Canada Secretariat's (2007 p. 38) recommended social time preference value of 3%. The resulting benefit-cost ratio is 3:1, that is, \$3 saved per added \$1 of construction cost. The table shows that if one chooses other parameter values, the benefit-cost ratio can be as low as 1 or as high as 7, considering these alternative choices:

1. Insurer perspective: Let us assume the insurer's retention rate from year to year is about  $R = 0.90$ , and that the insurer has a discount rate based in the current real opportunity cost of withdrawing capital from the real estate market (8.5%) minus inflation (2%), for a real discount rate of 6.5%.
2. Homeowner perspective: Homeowners might only consider benefits over a 5-year remaining tenure in their current house. Their discount rate might reasonably be taken as their real cost of borrowing, i.e., the mortgage interest rate minus inflation, currently 1%.
3. Different planning periods. The base case is a 20-year life of new shingles, but they could last as little as 10 or as many as 30 years.
4. Different discount rates. One might consider the homeowner's real cost of borrowing (1% as noted above) or the Treasury Board of Canada Secretariat (2007 p. 37) recommended cost of extracting funds from capital markets, 8%.
5. Different hazard. The base case reflects a Calgary neighborhood that experiences 2.4 hail days per year. One can consider lower hazard: a place 30 km east of Calgary that experiences 1.0 hail days per year, or a near-worst-case location 100 km northwest of Calgary that experiences 5.7 hail days per year.
6. Different shingle products. The base case is a class-4 shingle that adds \$164 per square installation cost. But some impact-resistant products can add as little as \$14 per square or as much as \$241 per square.
7. Different house sizes. The base case has a 167-m<sup>2</sup> (1,800 ft<sup>2</sup>) roof, which requires 20 roofing squares, but one can consider the 16<sup>th</sup> and 84<sup>th</sup> percentile houses, with roofs of 13 and 30 square, respectively.

**Table 8. Benefit-cost ratio of using impact-resistant asphalt shingle roofing near Calgary, Alberta.**

| Unrated shingles        | Unrated shingles |          |         |          | Impact-resistant shingles |          |      |       |          |     |
|-------------------------|------------------|----------|---------|----------|---------------------------|----------|------|-------|----------|-----|
|                         | Freq             | Severity | EAL     | PV       | Freq                      | Severity | EAL  | PV    | B        | BCR |
| Societal base case      | 0.27             | \$2,500  | \$690   | \$10,400 | 0.018                     | \$1,200  | \$22 | \$340 | \$10,000 | 3   |
| Insurer perspective     | 0.27             | \$2,500  | \$690   | \$2,900  | 0.018                     | \$1,200  | \$22 | \$96  | \$2,800  | 1   |
| Homeowner               | 0.27             | \$2,500  | \$690   | \$3,400  | 0.018                     | \$1,200  | \$22 | \$110 | \$3,200  | 1   |
| Short planning period   | 0.27             | \$2,500  | \$690   | \$5,900  | 0.018                     | \$1,200  | \$22 | \$190 | \$5,800  | 2   |
| Long planning period    | 0.27             | \$2,500  | \$690   | \$13,600 | 0.018                     | \$1,200  | \$22 | \$440 | \$13,000 | 4   |
| Low discount rate       | 0.27             | \$2,500  | \$690   | \$12,500 | 0.018                     | \$1,200  | \$22 | \$410 | \$12,000 | 4   |
| High discount rate      | 0.27             | \$2,500  | \$690   | \$6,900  | 0.018                     | \$1,200  | \$22 | \$220 | \$6,600  | 2   |
| Low hazard (30 km E)    | 0.12             | \$2,500  | \$290   | \$4,400  | 0.008                     | \$1,200  | \$10 | \$140 | \$4,300  | 1   |
| High hazard (100 km NW) | 0.66             | \$2,500  | \$1,700 | \$25,100 | 0.044                     | \$1,200  | \$55 | \$820 | \$24,000 | 7   |
| Low-cost shingles       | 0.27             | \$2,400  | \$660   | \$9,900  | 0.018                     | \$1,000  | \$17 | \$260 | \$9,600  | 6   |
| High-cost shingles      | 0.27             | \$2,600  | \$700   | \$10,500 | 0.018                     | \$1,500  | \$27 | \$400 | \$10,000 | 2   |
| Smaller house           | 0.27             | \$1,600  | \$450   | \$6,700  | 0.018                     | \$800    | \$15 | \$220 | \$6,500  | 3   |
| Larger house            | 0.27             | \$3,800  | \$1,000 | \$15,500 | 0.018                     | \$1,900  | \$34 | \$510 | \$15,000 | 3   |

#### 4.5.2 Observations and interpretation of results

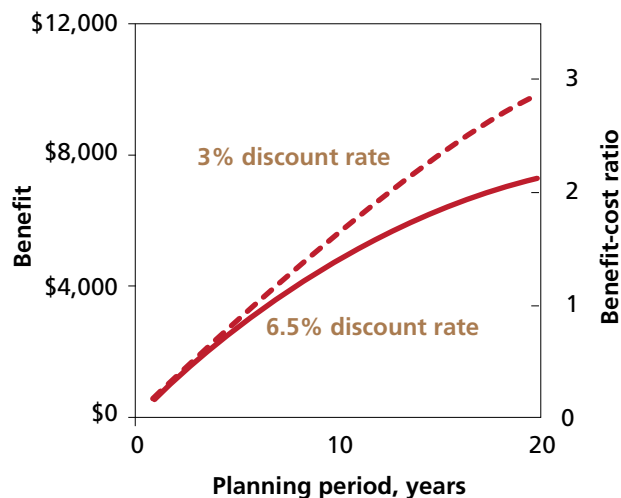
Some initial observations about the results. First, the BCR column suggests that no matter what decision situation or perspective one takes within the suite of options considered here, the impact-resistant shingles are cost effective. Every situation produces a benefit-cost ratio greater than 1.0, some as high as 7:1.

Second, the frequency columns show that, in Calgary, one can expect a storm that causes at least a little damage (1%) to an unrated roof once in four years (0.27 times per year). A class-4 impact-resistant roof has a much lower frequency: 0.018 times per year, or approximately once in 55 years, that is, about 15 times lower frequency.

Third, the table shows that impact-resistant shingles suffer about half as much damage in dollar terms when a damaging storm occurs. Changing from unrated shingles to class-4 shingles reduces the expected value of repair cost from \$2,500 (about 48% of the unrated roof's \$5,300 replacement cost) to \$1,200 (about 14% of the class-4 roof's \$8,700 replacement cost).

Fourth, planning period and discount rate both matter, as shown in Figure 14. Between the two, planning period matters more. Regardless of the discount rate, impact-resistant shingles save in the long run, paying for themselves within about 5 years in Calgary, with its 2.35 hailstorms per year. The benefit, benefit-cost ratio, and payback period decrease as frequency of hailstorms increases. More on how to scale results for other locations and other roofs sizes later.

**Figure 14.** How planning period and discount rate affect benefit and benefit-cost ratio.



Fifth, the claim frequency for unrated roofs may seem high at once every four years. It is unsurprising that the model might overestimate claim frequency. The model uses fragility functions that rely on laboratory tests with 90-degree impacts by ice spheres and steel balls, in some cases two impacts by large projectiles in the exact same spot. This situation contrasts with what actually happens in nature: (a) impacts by often less-dense hailstones (b) at angles that may be more glancing and less damaging, and where (c) much of the kinetic energy of impact is absorbed by crushing and fracturing of the hailstone, rather than being transferred to the shingle. For any or all these three reasons, and possibly for others, the frequency and severity figures might represent something of an upper bound.

It is unclear whether that means the benefit-cost ratios are higher or lower than a more exact model might predict, or that actuarial-quality loss data might reveal, or by how much. Much depends on how far off the estimates are from the true behavior of shingles, and on benefits that are not calculated here. The two classes (unrated and class-4 shingles) might differ in how conservative the estimates are. If the severity of both were high by the same amount, whether \$100 or \$500, the benefit would be the same and the benefit-cost ratio would be unchanged. One can imagine that a better estimate of true behavior in frequency, severity, or both could produce benefit-cost ratios that are higher, lower, or unchanged.

And the analysis omits several possible benefit sources, inclusion of which might raise the benefit-cost ratio.

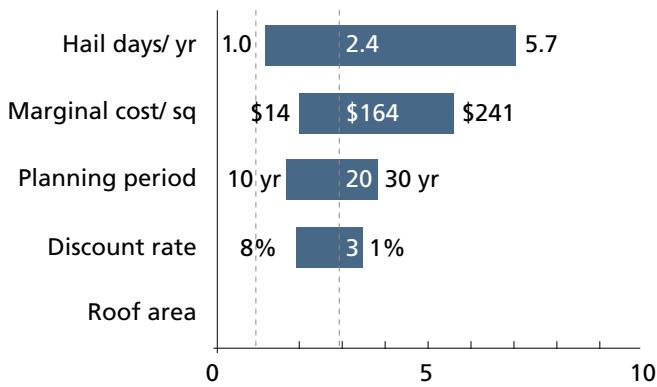
1. Lower claims-adjustment cost
2. Good will from the insured
3. The chance that subsequent owners will contract with the same insurer, and
4. Mutual benefit from widespread adoption. That is, the insurer may subsequently insure other properties that other insurers repaired with impact-resistant roofing.

### 4.5.3 Sensitivity tests

The analysis recognizes a variety of uncertain quantities within the model. Each uncertain model parameter can affect the benefit-cost ratio. This section examines how sensitive the benefit-cost ratios are to some of these uncertainties.

One can plot how the different variables reflected in Table 8 affect the result, to see visually how sensitive the benefits are to different assumptions. Figure 15 depicts the sensitivity of benefit-cost ratio (on the x-axis) to each of five variables. Each bar shows the how the benefit-cost ratio varies depending on the value of one of the variables. The top bar shows that BCR is most sensitive to location and therefore the hail hazard, a choice that can cause the BCR to vary between slightly more than 1:1 and as high as 7:1. BCR is next most sensitive to the shingle cost, then to the planning period, then the discount rate. The benefit-cost ratio is insensitive to roof size because cost and benefit both vary linearly with roof area: double the roof area and one doubles both the cost and benefit, so the ratio does not change. The tornado diagram shows that class-4 impact-resistant shingles are cost effective regardless of these parameter choices. Of course, more than one parameter value could be different from the base case, making the range of possible benefit-cost ratios broader than shown here.

**Figure 15.** Societal benefit-cost ratio for impact-resistant shingles in Hailstorm Alley, and its sensitivity to various inputs. The vertical dotted line at  $x = 1:1$  indicates breakeven: left is  $BCR < 1:1$ , right is  $BCR > 1:1$ .



### 4.5.4 Sensitivity to the fragility function

One can vary the fragility functions, but with important cautions about how much meaning the results have. A sensitivity test requires knowledge or judgment about how uncertain the parameter values are. But we have limited empirical knowledge about key uncertainties. Let us at least lay out some of our knowledge, make reasonable assumptions about their effects, and measure the results.

**Angle of attack.** Both fragility functions (for unrated and class-4 shingles) use 90-degree impacts by similar projectiles, which would both tend to overestimate damage. The kinetic energy of the hailstone relative to the roof when the hailstone impacts at a 45-degree angle might be about 70% that of the 90-degree impact. Impact energy increases approximately with diameter raised to the 4<sup>th</sup> power. A sphere of diameter  $X$  impacting at a 90-degree angle imparts about the same energy as one with  $1.1X$  diameter impacting at a 45-degree angle. Let us therefore reflect uncertainty in capacity associated with angle of attack with a uniform distribution with a domain of 1.0 to 1.1 times the estimated diameter of the sphere causing 50% failure probability (called the median capacity).

**Hailstone density.** The kinetic energy of a hailstone whose specific density is 0.4 g/ml (the low end estimated by Bilham and Relf 1937) could be less than 40% that of one with 0.92 g/ml density, because drag on a lighter hailstone reduces its terminal velocity relative to a heavier one with the same diameter. That means that it might take a less-dense hailstone perhaps 20% larger in diameter to cause equivalent damage. Let us reflect that uncertainty with a uniform distribution over 1.0 to 1.2 times the median capacity.

**Method-C failure probability (class-4 shingle only).** The true failure probability of the class-4 shingle when it is impacted by the 51-mm spheres might differ from 0.01; it could realistically be much higher or lower. Let us reflect that uncertainty with a uniform distribution of 0.8 to 1.2 times median capacity.

**Temperature and age.** Shingle failure probability could be affected by temperature and age, with colder and older things generally, but not always, being more damageable. Let us reflect that uncertainty with a uniform distribution over 0.8 to 1.0 times the median capacity.

One could reasonably make different choices for all these measures of uncertainty – different distribution shapes, different bounds, etc. – but without evidence, the foregoing choices seem at least reasonable.

**Result: slightly high median and slightly higher uncertainty.** Without showing the math, a numerical integration over these exogenous (not previously modeled) and uncorrelated variables suggests an approximately normally distributed median capacity with mean of 1.04 times the currently estimated value and standard deviation about 0.09 in the case of the unrated shingle and 0.15 in the case of the class-4 shingle.

Should we increase the median and uncertainty? We have already increased both the uncertainty and the median capacity of the unrated shingle to account for exogenous uncertainties like these. Without quantifying the possible sources, we raised the uncertainty from 0.09 to 0.25, more than enough to account for the 0.09 addition here. We raised the median capacity by more than the factor of 1.04. It therefore seems safe to say that the fragility function for the unrated shingle already accounts for these and other exogenous uncertainties.

The fragility function for the class-4 shingle already has a logarithmic standard deviation of 0.4, much more than the 0.15 calculated here. Uncertainties like these do not sum directly, but add through the square root of the sum of their squares. Doing so here would raise the logarithmic standard deviation of capacity from 0.40 to 0.43. Since the value of 0.4 was arrived at by judgment (see Porter et al. 2007 for more detail), the change would add only illusory accuracy.

The fragility function for the class-4 shingle has a median capacity that already reflects an extrapolation from 1% failure probability when impacted by a 51-mm sphere to 50% failure probability using this reasonably large uncertainty of 0.4. The median was 2.54 times the rated sphere diameter, so an increase by an additional 4% again seems like illusory accuracy.

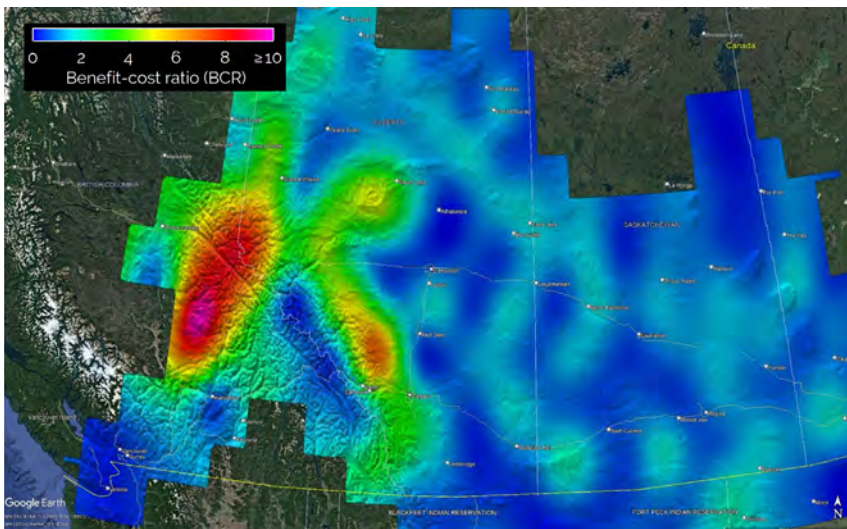
In short, one could modify the fragility functions to bring these previously exogenous variables into the damage model, but doing so does not seem justified, would provide illusory accuracy, and would effectively double-count their effect. It would be more defensible to perform better laboratory tests than to apply the somewhat arbitrary adjustments suggested here.

#### 4.5.5 Effect of geographic location on frequency and benefit-cost ratio

By the math presented here, the benefit-cost ratio varies in direct proportion to the number of hail days per year, differing only by a constant factor that depends on the impact rating and cost of the shingles. Under baseline conditions (3% social time preference and 20-year shingle life), the benefit-cost ratio is about 1.25 times the number of hail days per year.

Figure 16 and Figure 17 show the cost-effectiveness of impact-resistant shingles. They have a benefit-cost ratio greater than 1.0 (light blue colors or warmer in the map) across much of the Canadian west, especially on the east slope of the Canadian Rockies from Banff to Slave Lake, AB, and on the west slope between about Kamloops and Prince George, BC.

**Figure 16.** Benefit-cost ratio for class-4 impact-resistant asphalt shingles near Hailstorm Alley.



**Figure 17.** Benefit-cost ratio for class-4 impact-resistant asphalt shingles across much of the nation.

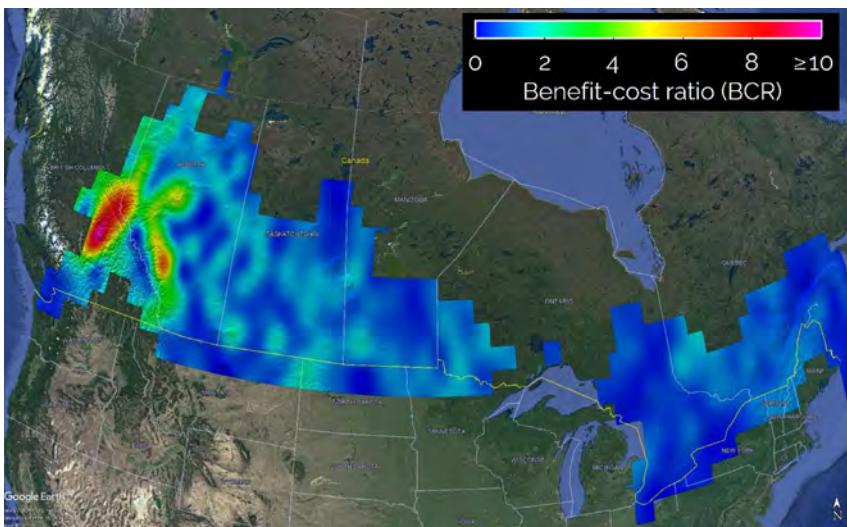
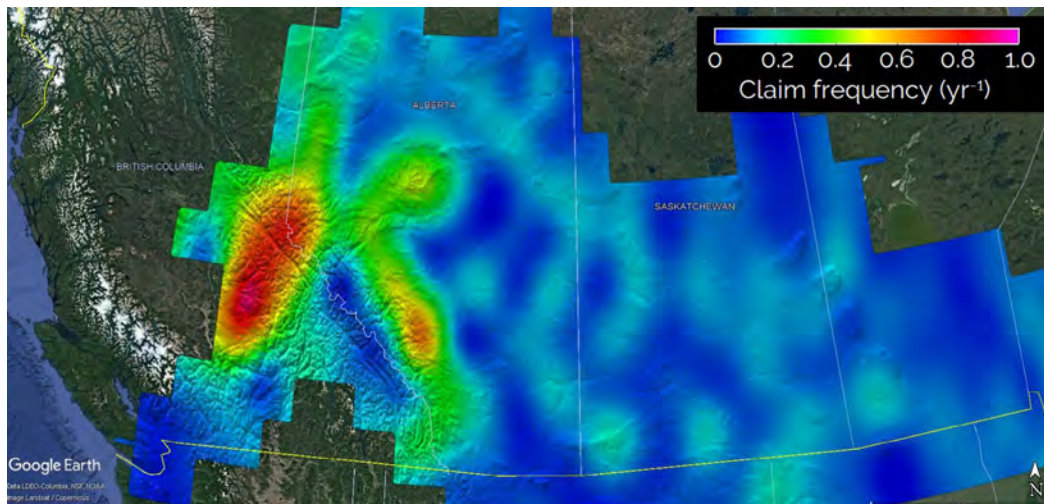


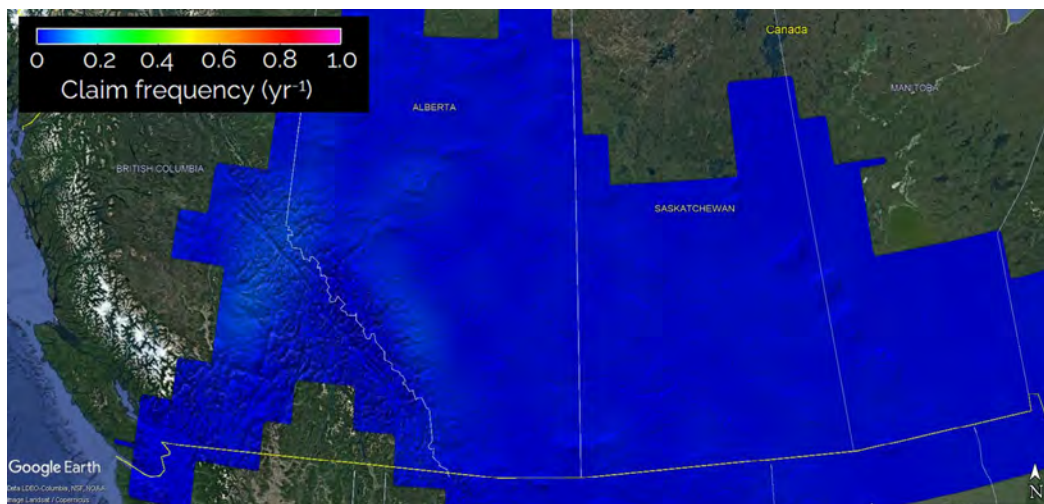
Table 8 and Figure 18 show the claim frequency in Calgary is 0.27 per year for unrated shingles, meaning that about once every four years, at least 1% of the shingles on an unrated roof would suffer cosmetic damage or a breach of their moisture barrier. Table 8 and Figure 19 show that installing an impact-rated roof in Calgary causes the claim frequency to drop by a factor of 15, from 0.27 to 0.018, or about one claim in 55 years.

Severity does not change geographically: about \$2,500 for the unrated roof, \$1,200 for the impact-resistant roof. Recall that the conservative nature of the fragility tests – 90-degree impacts by ice spheres and steel balls – may tend to over-estimate damage, so these frequency and severity estimates may represent something more like an upper bound.

**Figure 18.** *Insurer claim frequency for unrated asphalt shingles near Hailstorm Alley.*



**Figure 19.** *Insurer claim frequency for class-4 impact-resistant asphalt shingles near Hailstorm Alley.*



#### **4.6 Climate change**

The foregoing calculations ignore climate change. Recall that Raupach et al. (2021) estimate 7% increase in 20-mm hail per 1C warming, 21% for 35-mm hail, and 146% for 50-mm hail in the Canadian Rockies. Etkin's (2018) data span from 1977 to 2007, suggesting a baseline year of perhaps 1992 against which to measure warming.

Under representative concentration pathway (RCP) 8.5, ClimateData.ca estimates that Calgary will warm by about +2C in the next 30 years relative to 1992, suggesting an increase in hailstorm occurrence frequency (and therefore benefit-cost ratio) on the order of 14%, too small to make much difference in the benefit-cost ratios shown in Table 8 and the maps.

On the other hand, also recall that Cao (2008) found that hailstorm frequency approximately doubled between 1979 and 2002 with an increase of 0.7C in Ontario. There does not appear to be sufficient consensus yet to conclude that hailstorm frequency will double in Hailstorm Alley.



## 5. Conclusions

Let us now reflect what we have learned about the questions we sought to answer.

### 5.1 Successful creation of a performance-based engineering method for hail damage

This work presents a new performance-based engineering methodology to estimate the costs and benefits of installing impact-resistant roofing on buildings that are subject to hail. The methodology seems to work. It allows one to model the behavior of roofs of any arbitrary size, location, and other design attributes. It accounts for hail hazard including all of its variability in storm frequency, hitrate, duration, hailstone size distribution, and climate change. It estimates roof damage with empirically derived fragility functions that model the uncertain capacity of roofing shingles to survive impact by various size hailstones. It models the loss measure that matters most: repair cost.

This study illustrates some of the great strengths of performance-based engineering: it measures performance in terms that stakeholders care about (here, repair cost), as opposed to less-relatable measures such as passing prescriptive code requirements. It breaks the problem of the performance of an element of the built environment into tractable analytical stages, each of which can be tested in a laboratory or otherwise handled by standard scientific methods, without waiting for vast quantities of actuarial data to be made available and collected after rare catastrophic events. The present work did not explore another feature of performance-based engineering: the ability to quantify and propagate uncertainty through every analytical stage, but that could be done with modest additional effort.

### 5.2 The business case for an insurer to rebuild stronger homes

For an average-sized house in Calgary, benefit-cost analysis suggests that it can make financial sense for an insurer to pay to replace non-rated shingles with class-4 impact-resistant shingles. A class-4 impact-resistant roof for an average-sized house adds about \$3,400 to the cost of the roof, relative to an unrated roof. It reduces the claim frequency by about 15 times and the claim severity by half. It saves about \$4,200 over the life of a policy with 90% annual retention, for a benefit-cost ratio (BCR) of \$4,200/\$2,800, or 1.2:1.

The insurer's BCR of 1.2:1 suggests that an insurer who pays to rebuild stronger homes in Calgary with a class-4 roof will more than break even. It is cost effective for insurers to replace non-rated shingles with class-4 shingles anywhere with at least 2 hailstorms per year.

### 5.3 The societal business case for impact-resistant roofs

Society's viewpoint differs from the perspective of an insurer. From the larger perspective, one can consider the life of the roof (say 20 years) and a lower discount rate (the social time-preference rate of 3.0%). From this perspective, an impact-resistant roof appears to be far more cost effective, with a BCR up 10:1 for in some places. Impact-resistant shingles pay for themselves on average within about 5 years in Calgary, faster in locations with more-frequent hailstorms.

However, society does not make mitigation decisions, people do, in this case the developer or owner. If that decision-maker's interests do not align with society's – if the decision-maker pays and others benefit– then the decision-maker is unlikely to choose an impact-resistant roof. Possibly a set of insurance, grant, and market incentives like those suggested by Multi-Hazard Mitigation Council (2020) could better align stakeholder and societal interests and increase uptake.

## 5.4 The results scale

All of the costs and benefits of installing an impact-resistant roof scale with roof size, hailstorm frequency, or both. To estimate the quantities in Table 8 for a different roof size  $A$  or for a different location, find the roof size in roofing squares ( $A$ ). Find the hailstorm frequency for that location  $f_h$ , (e.g., from Figure 7). Pick the row in Table 8 that most closely matches the decision situation you care about (e.g., societal base case or insurer perspective), and apply Equations (41) through (47) to the quantities in that row.

$$\text{Cost} = \$3,400 \times \frac{A}{20} \quad (41)$$

$$\text{Claim frequency} = (\text{Freq in Table 8}) \times \frac{f_h}{2.35} \quad (42)$$

$$\text{Claim severity} = (\text{Severity in Table 8}) \times \frac{A}{20} \quad (43)$$

$$\text{Expected annualized loss} = (\text{EAL in Table 8}) \times \frac{A}{20} \times \frac{f_h}{2.35} \quad (44)$$

$$\text{Present value of future losses} = (\text{PV in Table 8}) \times \frac{A}{20} \times \frac{f_h}{2.35} \quad (45)$$

$$\text{Benefit} = (\text{B in Table 8}) \times \frac{A}{20} \times \frac{f_h}{2.35} \quad (46)$$

$$\text{Benefit-cost ratio} = (\text{BCR in Table 8}) \times \frac{f_h}{2.35} \quad (47)$$

## 5.5 Study limitations

All studies are limited in their objectives and results. Here are some particularly notable limitations that might be addressed in later study.

1. **No BCRs for other impact-resistance ratings, other roofing types, cladding, or vehicles.**

This study developed a performance-based engineering method to estimate the costs and benefits of class-4 impact-resistant asphalt-shingle roofing consistent with ICLR's HailSmart advocacy of class-4 roofs. The present study focused on residences, but it applies to commercial or other buildings with asphalt-shingle roofing. One can use its methods to quantify the benefit-cost ratio of class-3 or other asphalt shingles, metal roofs, or other roofing products. It could be used to judge changes in siding with additional fragility data on siding materials and products.

2. **Limited fragility information.** The study develops method-C fragility functions for impact-resistant shingles, based solely on pass/fail tests of the size of sphere that the shingle is capable of resisting ("capable" provides the  $c$  in method C). Method C uses a standard assumed value of uncertainty ( $\beta = 0.4$ ) that reflects this important data limitation. Laboratory testing that reflects the variability of real-world hail impacts could overcome this limitation and improve our confidence in a repetition of this study.

3. **No empirical validation.** The performance-based engineering method is called a forward analysis, meaning that the output is purely analytical, as opposed to actuarial or based on other observational data. It exercised its methodology for a sample house with asphalt shingle roofing in Calgary as an interesting proof of concept. This analysis presents no attempt to validate the findings, e.g., through comparison with storm experience data, although that could be done.
4. **Demand surge will occur.** The pilot study uses consequence functions (which relate damage to loss) that ignore possible demand-surge effects that very large catastrophes impose on the construction market, temporarily raising repair prices. A rise in labour costs would lead to higher estimated losses both to unrated roofs and to impact-resistant shingles. The relative losses would rise in proportion to labour costs, but since unrated roofs suffer more damage than impact-resistant roofs, they would also have a greater increase in repair cost. The avoided loss of using impact-resistant shingles would increase, meaning that the benefit would be greater, and the benefit-cost ratio would also be greater.
5. **Insurer-specific depreciation policies are not reflected.** As noted earlier, at least some insurers reduce claim payments for older roofs. The depreciation shifts some repair costs from the insurer to the owner. Because the benefits reflect reduction in repair costs, the reduction in repair costs for older roofs actually shifts benefits from the insurer to the owner. That shift is not reflected in the results presented here.
6. **All costs change over time and differ geographically.** Costs and benefits presented here are based on available sources. Costs vary over time as labour and material prices fluctuate. They also vary geographically. However, it seems more useful and practical to estimate current costs and benefits and explain their sources and assumptions, rather than to attempt to provide some sort of universal estimate that will be accurate everywhere and over all time, or to despair of the possibility of providing quantitative results.

## 5.6 Future research

Most of the limitations listed above could be reduced or eliminated with further study. Several examples:

1. **Improve shingle fragility functions with laboratory testing to failure.** One could improve the fragility functions with laboratory testing of shingles using method A (actual failure excitation), in which one experimentally observes the actual value of hailstone size (or steel sphere size) that causes failure. To produce realistic fragility functions, the experiments could better reflect real-world variability in impact of hailstones on roofs: the angle at which spheres impact the roof, the kinetic energy of the sphere, its coefficient of restitution, and possibly other variables. The results might show greater resistance of shingles to realistic hailstone impacts than the method-C fragility functions based on rating tests.
2. **Perform empirical validation.** We attempt to validate the findings presented here through comparison with storm experience data. Such an effort could be undertaken in collaboration with claims adjusters after a hailstorm. We would observe damage after a hailstorm from a sample of at least several dozen roofs whose impact ratings and maximum hailstone sizes were observed.

3. **Calculate BCRs for classes 1, 2, and 3 shingles, and for transitioning from 1 to 4, 2 to 4, etc.** We possess most of the data required to perform these calculations. We lack knowledge of class-1 and class-2 roofing shingles, especially their material costs.
4. **Calculate BCRs to improve siding, protect vehicles, and for hail seeding.** We could perform similar studies about the cost-effectiveness of impact-resistant siding, for temporary shelters that protect vehicles, and for hail seeding. These would require fragility functions for the siding, shelters, and crops. A hail-seeding benefit-cost analysis would require knowledge of the changes in hitrate, maximum hailstone diameter, and hailstone size distribution in a seeded storm.
5. **Incentivization.** Better roofs benefit several stakeholders. The present insurer enjoys about 52% of the avoided future losses (assuming 90% annual retention rate, 6.5% discount rate, and a 20-year life of the roof). Subsequent insurers also benefit: the second insurer enjoys about 17% of the avoided future losses, the third, about 9%, etc. Present and future homeowners also benefit. If their insurer offers a premium incentive for lower risk, homeowners may save monetarily, but they also suffer less nuisance and interruption. Only one of these stakeholders will pay for the roof. ICLR could work with insurers, homeowners, and perhaps others to design incentives that would share the cost of better roofs more fairly, more in proportion to benefits.

## References cited

- American Meteorological Society (2012). Hail. *Glossary of Meteorology*. <https://glossary.ametsoc.org/wiki/Hail> [accessed 18 Oct 2021]
- Asphalt Roofing Manufacturers Association (2021). *A Simple Guide to Understanding Your Asphalt Shingle Roofing System*. Forest Hill, MD. <https://www.asphaltroofing.org/a-simple-guide-to-understanding-your-asphalt-shingle-roofing-system/> [accessed September 24, 2021]
- Applied Technology Council (2012). *Seismic Performance Assessment of Buildings Volume 1 – Methodology FEMA P-58-1*. Federal Emergency Management Agency, Washington DC, <http://goo.gl/QN8AQz>
- Awondo, S., Hollans, H., Powell, L., and Wade, C. (2016). *Estimating the Effect of FORTIFIED Home Construction on Home Resale Value*. University of Alabama, 6 p.
- Awondo, S., Hollans, H., Powell, L., and Wade, C. (2019). Estimating the effect of wind loss mitigation on home value. SSRN, 29 p. [https://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=3330193](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3330193) [accessed September 26, 2021]
- Bilham, E.G., and Relf, E.F. (1937). The dynamics of large hailstones. *Quarterly Journal of the Royal Meteorological Society*, 63 (269): 149-162, <https://doi.org/10.1002/qj.49706326904> [accessed November 9, 2021]
- Borland, S.W. (1977). Hail suppression: progress in assessing its costs and benefits. *Hail: A Review of Hail Science and Hail Suppression*, 155-179.
- Brown-Giammanco, T.M., Giammanco, I.M., and Estes, H.E. (2021). New asphalt shingle hail impact performance test protocol and damage assessment. *Natural Hazards Review* 22(4): 04021050, DOI:10.1061/(ASCE)NH.1527-6996.0000509
- California Residential Mitigation Program. (2020). *About EBB Earthquake Brace + Bolt*. <https://www.earthquakebracebolt.com/Content/AboutEBB> [accessed October 23, 2020]
- Canada Press (2014). Damage from Alberta hailstorm pegged at \$450M. *Global News*, Sept 4, 2014, <https://globalnews.ca/news/1544920/damage-from-alberta-hail-storm-pegged-at-450m> [accessed December 6, 2021]
- Cao, Z. (2008). Severe hail frequency over Ontario, Canada: Recent trend and variability. *Geophysical Research Letters*, 35(14), doi:10.1029/2008GL034888
- Cecil, D.J. and Blankenship, C.B. (2012). Toward a global climatology of severe hailstorms as estimated by satellite passive microwave imagers. *Journal of Climate*, 25(2), 687-703, <https://doi.org/10.1175/JCLI-D-11-00130.1> [accessed 27 Sep 2021]
- CertainTeed (2022). *Categories of Asphalt Roofing Shingles*. <https://www.certainteed.com/residential-roofing/categories-asphalt-roofing-shingles/> [accessed February 27, 2022].
- Changnon, S.A., Farhar, B.C., and Swanson, E.R. (1978). Hail suppression and society. *Science*, 200(4340), 387-394.
- ClimateData.ca (2021) ClimateData.ca.
- City of Calgary (2022). *Resilient Roofing Rebate Program*. <https://www.calgary.ca/pda/pd/home-building-and-renovations/hail-in-calgary.html> [accessed February 23, 2022]
- CSA Group (2016). *Standard CSA A123.5 Asphalt Shingles Made from Glass Felt and Surfaced with Mineral Granules*. Toronto, ON 21 p.
- Etkin, D. (2018). *Hail Climatology for Canada: An Update*. Institute for Catastrophic Loss Reduction, Toronto, ON, 40 p. <https://www.iclr.org/wp-content/uploads/2018/03/hail-climatology-for-canada-an-update.pdf> [accessed September 27, 2021]
- Federal Emergency Management Agency (1994). *Seismic Retrofit Incentive Programs: A Handbook for Local Governments*, FEMA 254. Washington, DC, 246 p.

- FM Approvals (2005). *Specification Test Standard for Impact Resistance Testing of Rigid Roofing Materials by Impacting with Freezer Ice Balls*. Class Number 4473. 10 p.
- Fraille, R., Castro, A., Lopez, L., Sanchez, J.L., and Palencia, C. (2003). The influence of melting on hailstone size distribution. *Atmospheric Research* 67-68: 203-213
- Gonzalez, G. (2007). Mexico: an evolution. *Professional Roofing*. <https://www.professionalroofing.net/Articles/Mexico—n-evolution--02-01-2007/1010> [accessed December 2, 2021]
- Grieser J., and Hill, M. (2019). How to express hail intensity—modeling the hailstone size distribution. *Journal of Applied Meteorology and Climatology* 58 (10): 2329–2345. <https://doi.org/10.1175/JAMC-D-18-0334.1> [accessed October 22, 2021]
- Groom, S. (2010). Will your next asphalt roof last a lifetime? *Fine Home Building* 214: 61-65, <https://www.finehomebuilding.com/membership/pdf/5614/021214061.pdf> [accessed November 12, 2021]
- Haag Engineering Co. (2006). *A White Paper: Hail Damage to Composition Shingles*. Flower Mound, TX, 3 p. <http://haagglobal.com/am-site/media/white-paper-hail-damage-to-composition-roofs-2006.pdf>
- Haag Research & Testing (2020). *A White Paper: Impact Testing of Impact-Resistant Shingles*. Flower Mound, TX, 5 p. <https://haagglobal.com/am-site/media/a-white-paper-on-impact-resistant-shingles---final-6-8-2020.pdf>
- Hanscomb Ltd. (2020). *Hail Costing Template 5566 03072020*. Unpublished, for ICLR. Hamilton, ON.
- Heymsfield, A.J., Giammanco, I.M., and Wright, R. (2014). Terminal velocities and kinetic energies of natural hailstones. *Geophysical Research Letters* 41, 8666-8672, doi:10.1002/2014GL062324
- Institute for Catastrophic Loss Reduction (2018). *Protect Your Home from Hail*. Toronto, ON. [https://www.iclr.org/wp-content/uploads/2021/04/ICLR\\_Hail-2020\\_E\\_2021.pdf](https://www.iclr.org/wp-content/uploads/2021/04/ICLR_Hail-2020_E_2021.pdf) [accessed January 6, 2022]
- Institute for Catastrophic Loss Reduction (2021). *The ICLR Strategic Plan 2022 to 2026*. Toronto, ON. [https://www.iclr.org/wp-content/uploads/2021/11/ICLR\\_Five-year-report\\_2021.pdf](https://www.iclr.org/wp-content/uploads/2021/11/ICLR_Five-year-report_2021.pdf) [accessed January 19, 2022]
- Insurance Institute for Business and Home Safety (2013). *IBHS Hailstorm Demonstration Results*. Richburg, SC, 4 p., [https://ibhs.org/wp-content/uploads/wpmembers/files/Hailstorm-Demonstration-Report\\_IBHS.pdf](https://ibhs.org/wp-content/uploads/wpmembers/files/Hailstorm-Demonstration-Report_IBHS.pdf)
- Insurance Institute for Business and Home Safety (2019). *IBHS Impact Resistance Test Protocol for Asphalt Shingles*. Richburg, SC, 39 p., <https://ibhs.org/wp-content/uploads/2019/06/ibhs-impact-resistance-test-protocol-for-asphalt-shingles.pdf>
- Insurance Institute for Business and Home Safety (2020). *Hail Impact Performance of Asphalt Shingles: at a Glance*. Richburg, SC, 2 p. <https://ibhs.org/wp-content/uploads/wpmembers/files/ibhs-hail-impact-at-a-glance.pdf>
- Kennedy, R.P., and Ravindra, M.K. (1984). Seismic fragilities for nuclear power plant risk studies. *Nuclear Engineering and Design* 79: 47-68
- Kim, E., and Gagnon, R.E. (2016). A preliminary analysis of the crushing specific energy of iceberg ice under rapid compressive loading. *Proc. 23rd IAHR International Symposium on Ice, Ann Arbor, Michigan USA, May 31 to June 3, 2016*, 11 p. <https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2465813/Kim%2band%2bGagnon%2bIAHR%2b2016.pdf?sequence=1&isAllowed=y> [accessed January 19, 2022]
- Laurie, J.A.P. (1960). *Hail and its Effects on Buildings*. Rep. No. 176. Pretoria, South Africa: Council for Scientific and Industrial Research. 11 p.
- Mann, R. (2021). Recalling the most damaging events from the hailstorm capital of Canada. *The Weather Network*. <https://www.theweathernetwork.com/ca/news/article/this-day-in-weather-history-september-7-1991-calgarys-tennis-ball> [accessed December 6, 2021]

- Marshall, T., and Herzog, R. (1999). Protocol for assessment of hail-damaged roofing. *Proceedings of the North American Conference on Roofing Technology, August 16-17, 1999, Toronto, Ontario*: 40-46, [https://www.researchgate.net/publication/327022554\\_Protocol\\_for\\_Assessment\\_of\\_Hail-Damaged\\_Roofing](https://www.researchgate.net/publication/327022554_Protocol_for_Assessment_of_Hail-Damaged_Roofing) [accessed November 3, 2021].
- Marshall, T.P., Herzog, R.F., and Morrison, S.J., (2004). Hail damage to asphalt roof shingles. *Proc. American Meteorological Society Annual Meeting 2004, January 10-15, 2004, Seattle, WA*, p. 9.4, <https://ams.confex.com/ams/pdfpapers/81091.pdf>
- Marshall, T.P., Herzog, R.F., Morrison, S.J., and Smith, S.R. (2002). Hail damage threshold sizes for common roofing materials. *21<sup>st</sup> Conference on Severe Local Storms, August 11-16, 2002, San Antonio, TX*. Vol 25, p 3.2, <https://ams.confex.com/ams/pdfpapers/45858.pdf>
- McLean, S. (2021). Canada's 2020 CRE returns worst since 1993: MSCI/REALPAC | *RENX – Real Estate News Exchange*. <https://renx.ca/2020-canadian-cre-return-worst-since-1993> [accessed December 6, 2021]
- Multi-Hazard Mitigation Council (2020). *A Roadmap to Resilience Incentivization*. Porter, K.A. and Yuan, J.Q., eds., National Institute of Building Sciences, Washington, DC, 33p. <https://www.nibs.org/page/resilienceroadmap>
- National Severe Storms Laboratory (ND). *Severe Weather 101 Hail Basics*. National Oceanic and Atmospheric Administration. <https://www.nssl.noaa.gov/education/svrwx101/hail/> [accessed 22 Sep 2021]
- Owens-Corning (2022). *Types of Roofing Shingles*. <https://www.owenscorning.com/en-us/roofing/tools/types-of-roofing-shingles> [accessed February 27, 2022]
- Pang, A. (1999). Disaster loss mitigation: Great balls of hail. Canadian Underwriter. <https://www.canadianunderwriter.ca/features/disaster-loss-mitigation-great-balls-of-hail> [accessed Nov 24, 2021]
- Perera, S. (2017). *Modeling Impact Actions of Flying and Falling Objects*. University of Melbourne. 253 p. [https://minerva-access.unimelb.edu.au/bitstream/handle/11343/194798/665853\\_Shihara%20Perera\\_Thesis\\_.pdf](https://minerva-access.unimelb.edu.au/bitstream/handle/11343/194798/665853_Shihara%20Perera_Thesis_.pdf) [accessed 23 Sep 2021]
- Perera, S., Lam, N., Pathirana, M., Zhang, L., Ruan, D., and Gad, E. (2018). Probabilistic modelling of forces of hail. *Natural Hazards* 91, 133–153 (2018). <https://doi.org/10.1007/s11069-017-3117-7> [accessed 23 Sep 2021]
- Porter, K.A. (2003). An overview of PEER's performance-based earthquake engineering methodology. *Proc. Ninth International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9) July 6-9, 2003, San Francisco, CA*. Civil Engineering Risk and Reliability Association (CERRA), 973-980, <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.538.4550&rep=rep1&type=pdf>
- Porter, K.A., Kennedy, R.P., and Bachman, R.E., (2007). Creating fragility functions for performance-based earthquake engineering. *Earthquake Spectra*. 23 (2): 471-489, <https://www.sparisk.com/pubs/Porter-2007-deriving-fragility.pdf> [accessed January 10, 2022]
- Porter, K.A., Scawthorn, C.R., and Sandink, D. (2021). *An Impact Analysis for the National Guide for Wildland-Urban Interface Fires*. Prepared for the National Research Council of Canada. Institute for Catastrophic Loss Reduction, Toronto, ON, 136 p., <https://doi.org/10.25810/rxtc-3p87>
- Porter, K.A., Alhumaidi, J., and Reed, Z. (in press). Do California house buyers value seismic retrofit? *Natural Hazards Review*. Accepted for publication February 1, 2022.
- Raupach, T.H., Martius, O., Allen, J.T. et al. The effects of climate change on hailstorms. *Nat Rev Earth Environ* 2, 213–226 (2021). <https://doi.org/10.1038/s43017-020-00133-9> file://c:\JobLib\Pub\Raupach\Raupach et al (2021) NREE The effects of climate change on hailstorms.pdf
- Robinson, E.D. (2016). Canadian Megadisasters: *An Exploration of Sensitivities and Implications for the Insurance Industry*. AIR Worldwide, 1 hr 28 min, <https://www.youtube.com/watch?v=pvD0ks4p63I> [accessed Nov 24, 2021]

- Roof Advisor (2021). *How Much Does a Roof Replacement Cost in the UK?* <https://www.roofadvisor.co.uk/how-much-does-a-roof-replacement-cost-in-the-uk> [accessed December 2, 2021]
- RSMMeans (2020) *Contractor's Pricing Guide: Residential Repair & Remodeling Costs with RSMMeans Data*. The Gordian Group, Inc., 321 p.
- Simmons, K.M., and Sutter, D. (2007). Tornado shelters and the housing market. *Construction Management and Economics*. 25: 1117-1124. <https://doi.org/10.1080/01446190701618299> [accessed October 10, 2021]
- Simmons, K.M., Kruse, J.B., and Smith, D.A. (2002). Valuing mitigation: real estate market response to hurricane loss reduction measures. *Southern Economic Journal*, 68(3): 660-671. <https://doi-org.colorado.idm.oclc.org/10.2307/1061724> [accessed October 9, 2021]
- Sonka, S.T., and Changnon Jr, S.A. (1977). A methodology to estimate the value of weather modification projects: an illustration for hail suppression. *Journal of Applied Meteorology and Climatology*, 16(7): 677-682.
- Sun, J., Lam, N., Zhang, L., Ruan, D., & Gad, E. (2015). Contact forces generated by hailstone impact. *International Journal of Impact Engineering*, 84, 145-158, <https://doi.org/10.1016/j.ijimpeng.2015.05.015>
- Swan, S.W. and Kassawara, R. (1998). The use of earthquake experience data for estimates of the seismic fragility of standard industrial equipment. ATC 29-1, *Proc of Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components*. Applied Technology Council, Redwood City, CA, 313-322
- Swanson, E.R., Sonka, S.T., Taylor, C.R., & van Blokland, P.J. (1978). An economic analysis of hail suppression. *Journal of Applied Meteorology*, 17(10): 1432-1440.
- TD Canada Trust. (2021) *Today's Mortgage Rates*. <https://www.td.com/ca/en/personal-banking/products/mortgages/mortgage-rates> [accessed December 6, 2021]
- Trading Economics (2021). *Canada Inflation Rate*. <https://tradingeconomics.com/canada/inflation-cpi> [accessed December 6, 2021]
- Treasury Board of Canada Secretariat (2007). *Canadian Cost-Benefit Analysis Guide Regulatory Proposals*. <https://www.tbs-sct.gc.ca/rtrap-parfa/analys/analys-eng.pdf> [accessed January 10, 2022]
- Underwriters Laboratory (2020). *UL Standard for Safety Impact Resistance of Prepared Roof Covering Materials*. Northbrook IL, 18 p.
- US National Weather Service (2010) NEW 1 Inch Hail Criteria. National Oceanic and Atmospheric Administration, [https://nws.weather.gov/products/PDD/OneInchHail\\_Oper\\_PDD.pdf](https://nws.weather.gov/products/PDD/OneInchHail_Oper_PDD.pdf) [accessed October 27, 2021]
- U.S. Nuclear Regulatory Commission (1975). *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants (WASH-1400) (NUREG-74/014)*. National Technical Information Service, Springfield VA.
- Wong, R.K., Chidambaram, N., Cheng, L., and English, M. (1988). The sampling variations of hailstone size distributions. *Journal of Applied Meteorology and Climatology*, 27(3), 254-260, [https://doi.org/10.1175/1520-0450\(1988\)027<0254:TSVOHS>2.0.CO;2](https://doi.org/10.1175/1520-0450(1988)027<0254:TSVOHS>2.0.CO;2) [accessed 18 Oct 2021]







Institute for Catastrophic Loss Reduction  
Institut de prévention des sinistres catastrophiques

**Toronto Office**

20 Richmond Street East  
Suite 210  
Toronto, Ontario, Canada  
M5C 2R9

📞 416-364-8677

📠 416-364-5889

**London Office**

Western University  
Amit Chakma Building  
Suite 4405  
1151 Richmond Street  
London, Ontario, Canada  
N6A 5B9

📞 519-661-3234

📠 519-661-4273

@ info@iclr.org

🌐 www.iclr.org

🌐 www.hail-smart.com

🌐 www.PIEVC.ca

📘 facebook.com/instituteforcatastrophiclossreduction

🐦 twitter.com/iclrcanada • twitter.com/citiesadapt

📺 youtube.com/iclrinfo

🌐 Search: Institute for Catastrophic Loss Reduction (ICLR)

🌐 www.basementfloodreduction.com

🌐 www.reduirelesinondationsdesous-sol.com

🌐 www.backwatervalueinstallation.com

