Assessing the Likelihood of Hail Impact Damage on Wind Turbines

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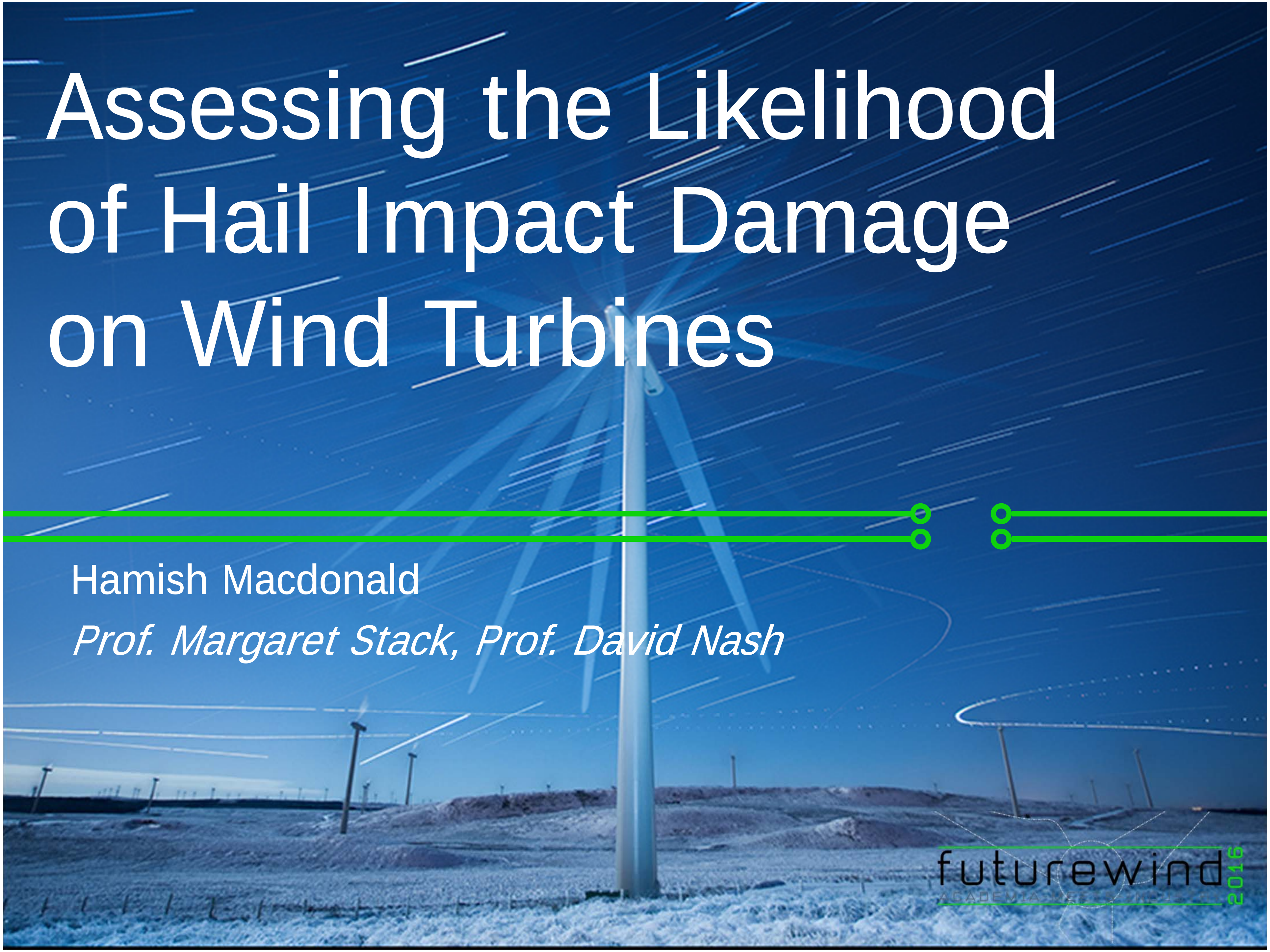
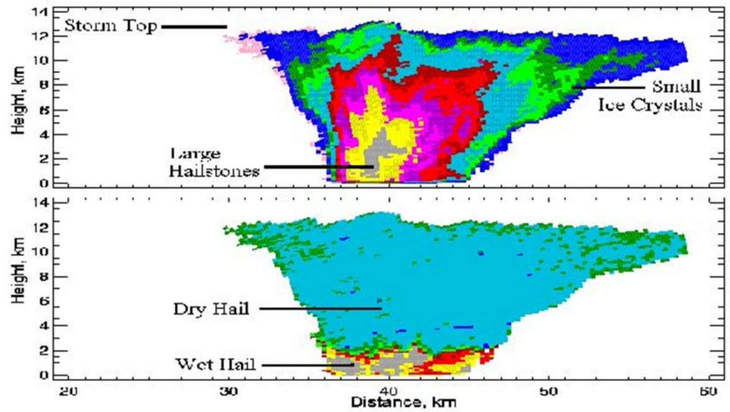


Environmental Conditions

- Temperature
- Salinity in the air
- UV radiation from sunlight
- Lightning
- Airborne particles
  - Sand and other small particles
  - **Hailstones**
  - Rain
- *An offshore environment requires additional consideration* – IEC 61400-1 international standard.



Impact of Erosion

- Increase in drag & decrease in lift production
  - Due to:
    - Degradation of aerofoil characteristics
    - Increased roughness
  - Results in a Decrease in annual energy production (AEP)
- Unbalanced Rotor
  - Waterlogged Blades
  - Vibrations
- Maintenance Concerns
  - Blade Repair
  - Full Replacement
  - Associated downtime
  - Offshore access

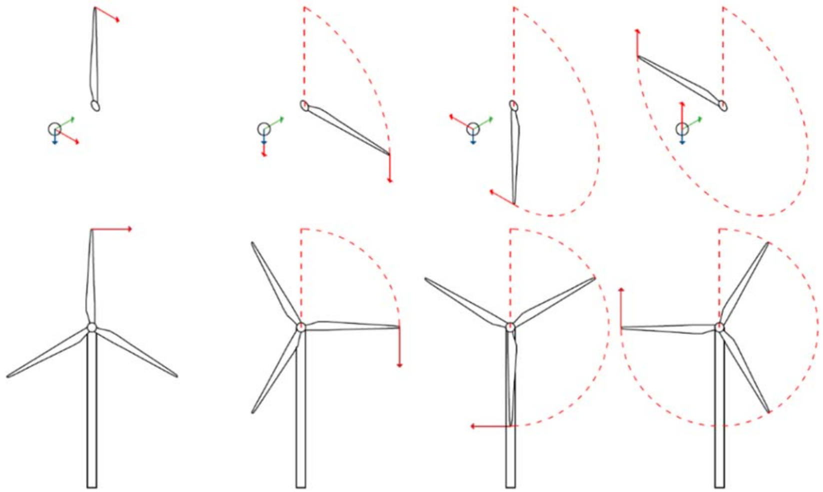
Table III. Effect of leading edge erosion on wind turbine blade performance as estimated by PROPID.

Condition	ΔC_d	ΔC_l	Avg wind speed m/s	AEP loss MWh/yr	AEP loss (%)
A1	+6%	−0.07	—	—	—
			7.05	383	−4.85
A2	+80%	−0.12	7.93	392	−4.10
			8.81	384	−3.49
A3	+150%	−0.15	—	—	—
B2	+150%	−0.16	—	—	—
			7.05	902	−11.42
B3	+200%	−0.14	7.93	930	−9.73
			8.81	917	−8.33
B4	+400%	−0.15	—	—	—
C3	+150%	−0.16	—	—	-
			7.05	1,858	−23.53
C4	+400%	−0.15	7.93	1,948	−20.38
			8.81	1,947	−17.68
C5	+500%	−0.17	—	—	—

"Effects of leading edge erosion on wind turbine blade performance" - Sareen *et al.* (2013)

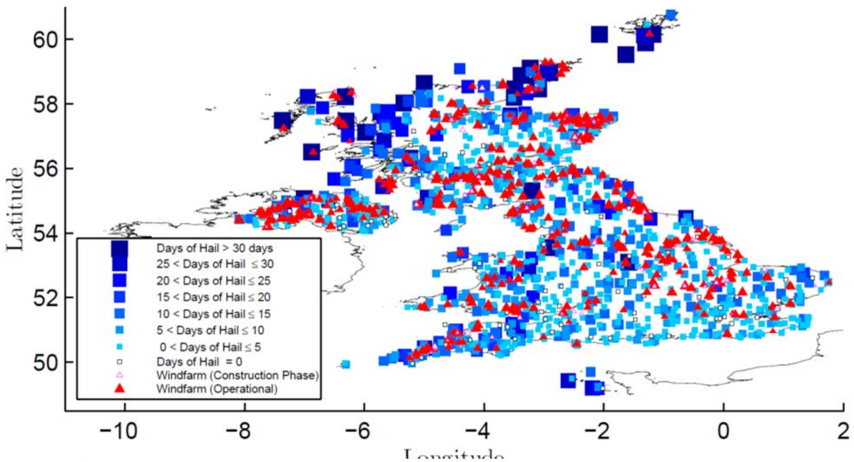
Methodology Outline

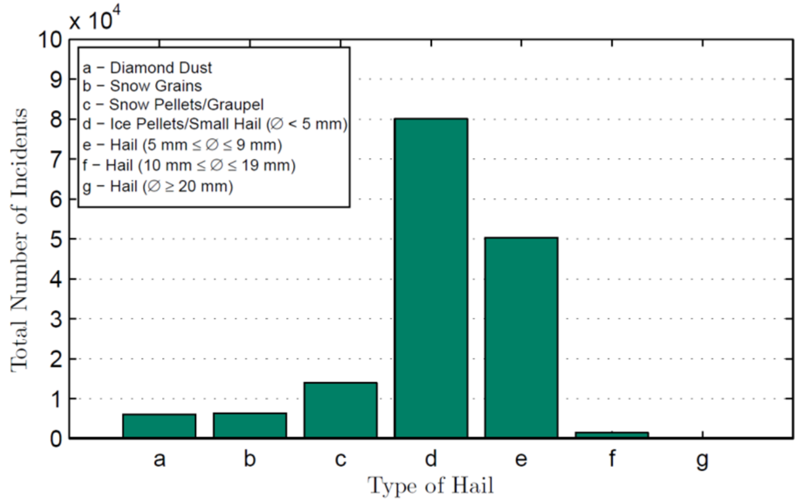
- Prior to testing and modelling hail erosion, important to understand practical scenarios and their likelihood.
  - **Impact Velocity** during hail events
    - Hailstone terminal velocity
    - Mean wind speed
    - Wind turbine rotational speed/tip speed
  - Other Hail Impact Considerations
    - Size distributions
    - Rates
    - Durations
    - Seasonality
    - Geographical Spread – Close to commercial wind farm sites

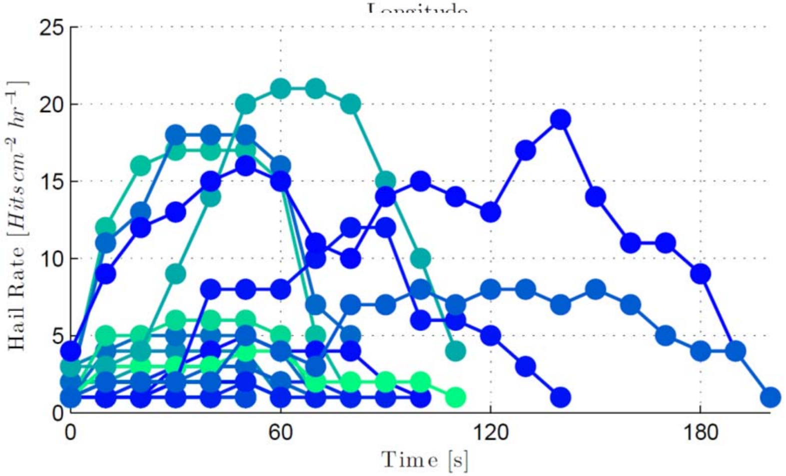


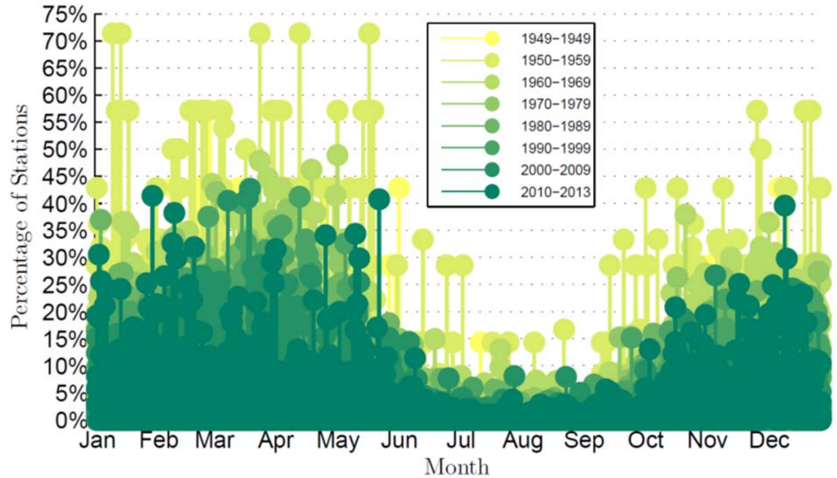
Weather Data

- Majority of stations subject to 0 < hail days ≤ 5 per year on average
- Approximately 2.26% of all MIDAS stations receive more than 30 days of hail per year on average.
- Development of Impact Profiles









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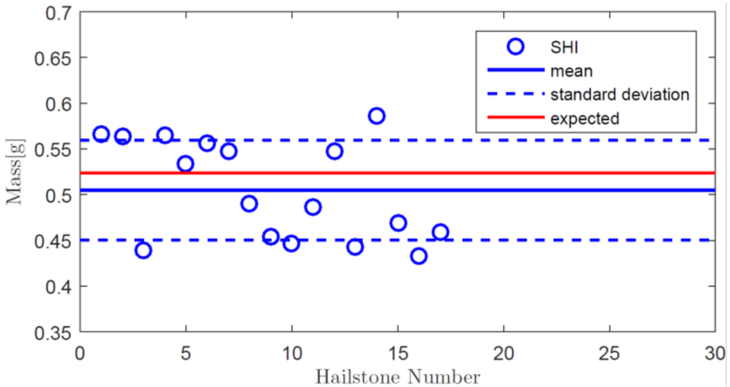
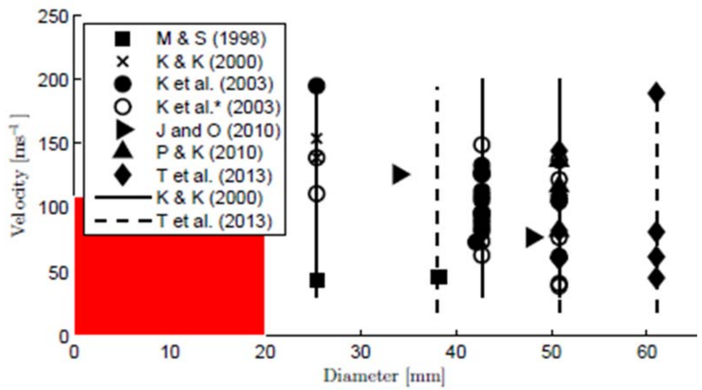
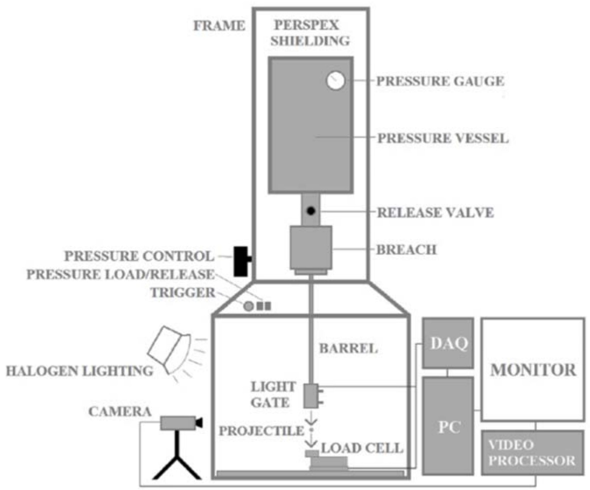
Hailstone Rig

- Capable of >100 m/s speeds
- Variables
  - SHI Diameter (Originally exclusively 10mm)
  - Velocity
  - Number of Impacts
    - Cumulative annual assessment
- Modifications
  - 5mm, 15mm, 20mm barrels (& SHI moulds)
  - Dynamic force transducer
  - Secure composite clamping arrangement
- Importance of consistency of projectiles
  - Temperature







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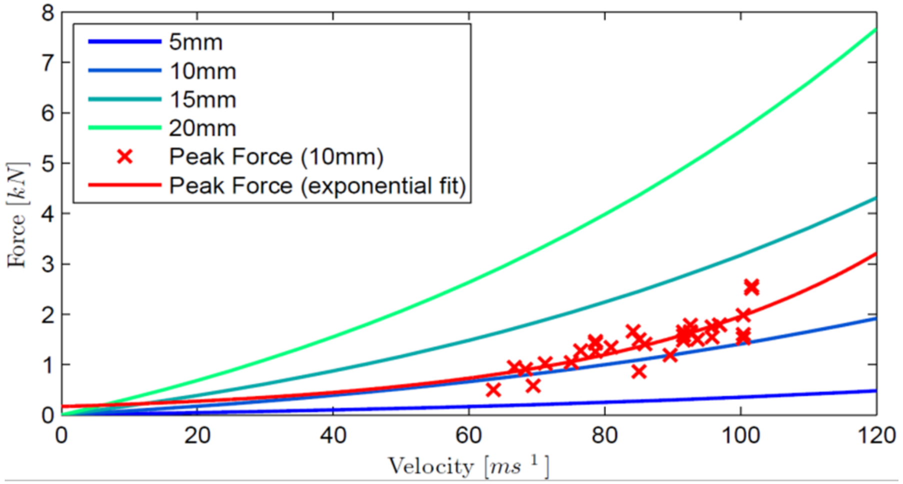
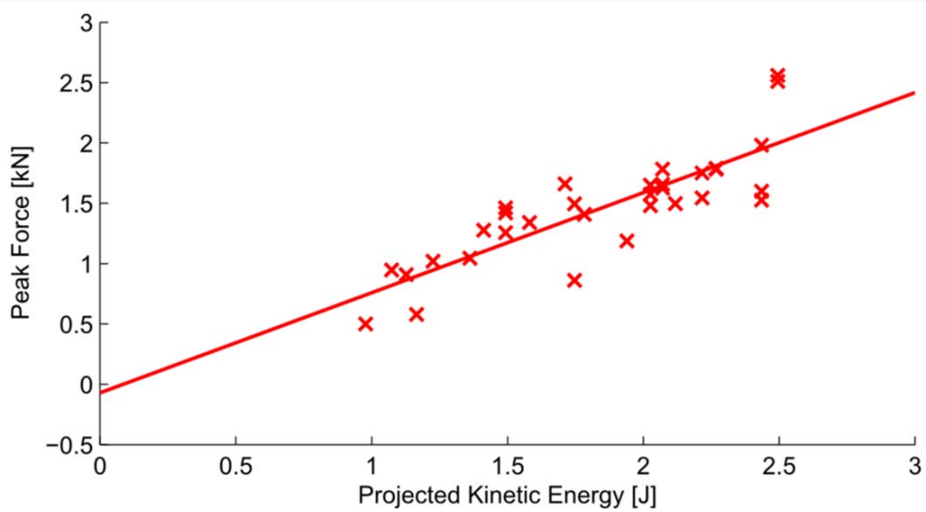
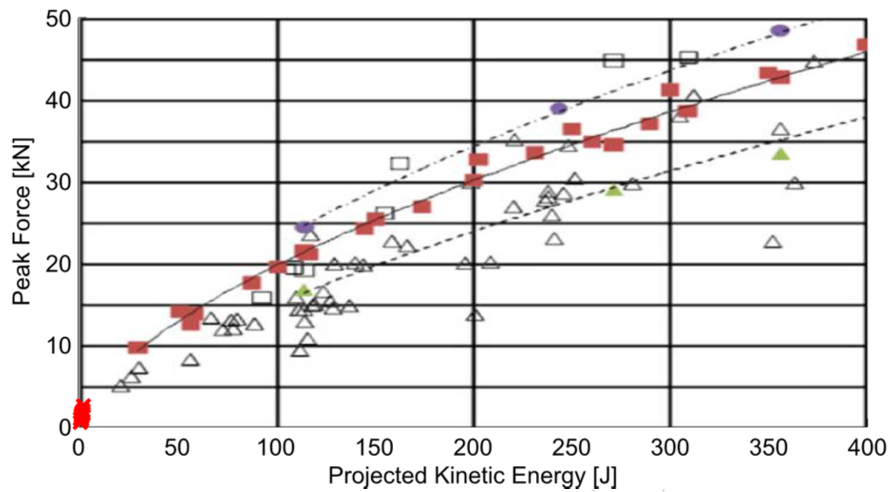
Initial Calibration/ Comparisons

- Peak Force vs. Velocity
  - Roisman and Tropea [2015]
  - $F \approx \frac{4\pi}{3} R_0^2 U_0 \rho^{\frac{1}{2}} Y^{1/2}$
- Peak Force vs. Kinetic Energy
  - Tipmmann *et al.* [2013]



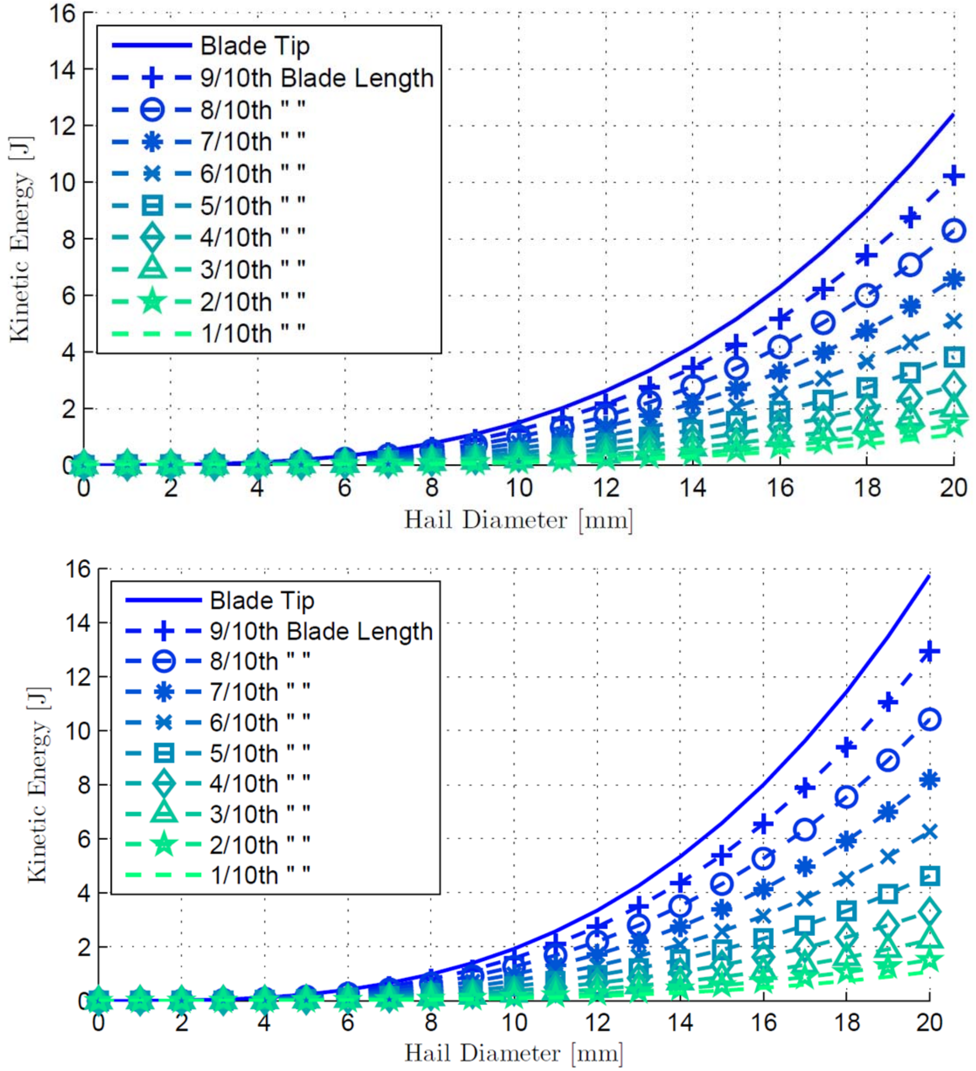




Impact Energy

- Aggregation of the separate contributions for a weather station with hail incidence for two different turbines.
  - $T_1=1/2\ mv^2$ for the different hail sizes of hail along discrete locations along the blade. One impact per hail event.
- Cumulative failure for threshold energy of 72–140 J for CFRP (Appleby Thomas *et al.)*
- Higher thresholds for glancing impact
- Gap in the literature for GFRP
  - Manufactured in-house

	Category				Total
	c	d	e	f	
2.3 MW Class IIa Onshore Turbine					
Mean Profile	0.0272 J	0.3721 J	1.9236 J	0.6307 J	2.9537 J
Extreme Profile	0.9302 J	4.0811 J	6.2477 J	4.5734 J	15.8325 J
6 MW Class Ia Offshore Turbine					
Mean Profile	0.0348 J	0.4767 J	2.4581 J	0.8013 J	3.7709 J
Extreme Profile	1.1915 J	5.2275 J	7.9836 J	5.8104 J	20.2130 J



Meteorological Conclusions

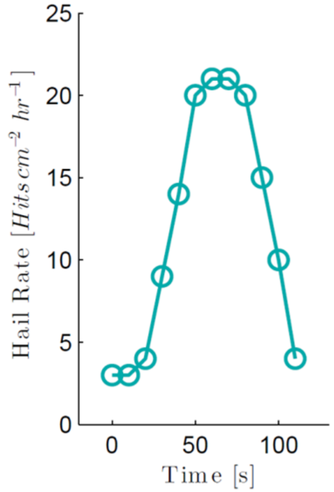
- Ice pellets/small hail (diameter < 5 mm) is the most frequent category of hail.
- Incidents involving diameters of hailstones greater than 20 mm are very rare events, with only 102 incidents recorded over the entire 65 year period.
- The majority of stations experience fewer than 5 days of hail a year (prevalence a lot less than rain).
- Two example experimental profiles developed
- Even for an extreme case study, signs of damage would not be expected until many years of operation.

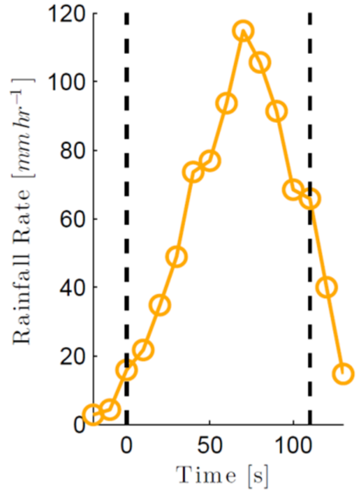
Ongoing Work

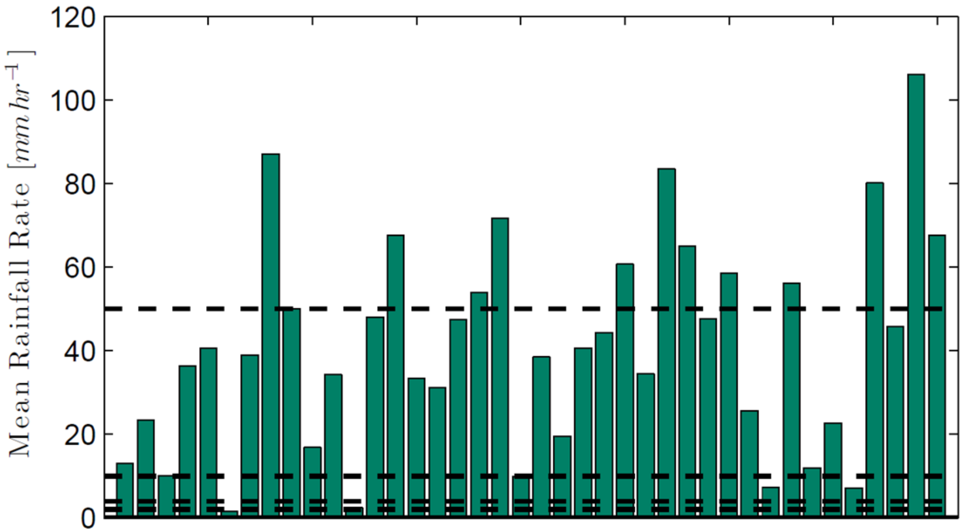
- Series of Experimental tests
  - Diameter vs. velocity vs. Number of impacts
- Potential variables
  - Impact angle
  - Hail composition (salt)
  - Composite thickness
- Composite inspection
  - Visual
  - Mass loss
  - SEM (Scanning electron microscope)
  - Compression strength after impact test (CAI)

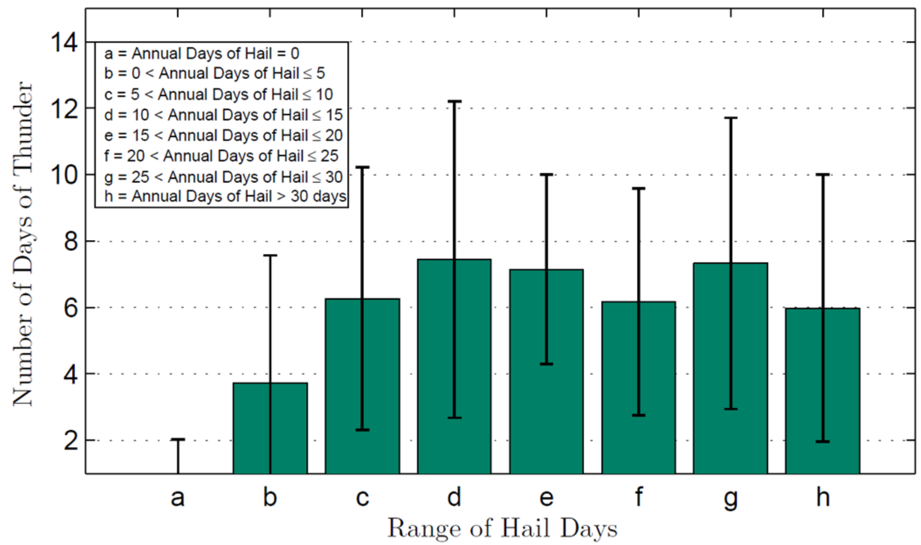
Hailstorms – not just hailstones

- 0 to 2 mmh^{-1} - slight
- 2 to 10 mmh^{-1} - moderate
- 10 to 50 mmh^{-1} - heavy
- > 50 mmh^{-1} - violent









Questions

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