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Quantifying ice ball impact behavior to strengthen PV module hail impact resilience

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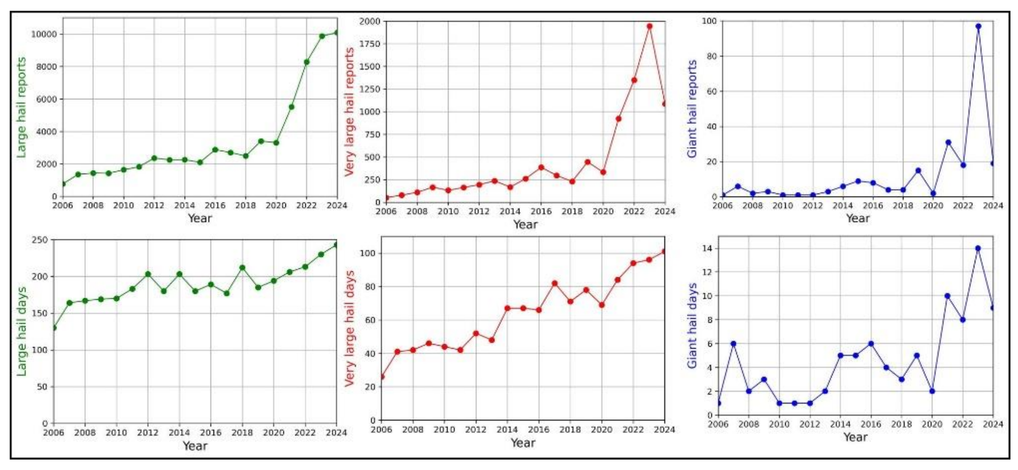
Motivation

Hailstorms are becoming more frequent and intense due to climate change, particularly in alpine regions. PV module resistance to hail impacts is being improved, as outlined by standards like IEC 61215 and Swiss VKF. As hailstones size and speed increase, enhanced safety margins are needed, and it can be achieved with upgraded hail test measures. The impact of hail simulated by standards with an ice ball must be examined. This study investigates impact velocity, impact angles and duration for ice balls with diameter ranging from 25 to 90 mm at speeds of 25, 50, 75 and 100 m/s and ice ball storage temperatures ranging from -4° to -28°C. Experimental data were analysed using dimensionless peak force and corresponding time as a function of dimensionless velocity and impact angle. Furthermore, compressive and indirect tensile strengths were studied in quasi-static and high strain rate regimes as a function of temperature. Based on these results, empirical relationships defined as functions of the impact velocity, sample size, dynamic tensile strength, density, and elastic wave speed of ice were analysed and compared with findings in the literature.

The study was conducted as part of the ongoing **ACHILLES project**, in collaboration with the Swiss Association of Cantonal Fire Insurance (ACFI). The project aims to develop guidelines for stakeholders in Switzerland, offering strategies to mitigate hail risk and enhance the resilience of PV systems. The research begins with a fundamental investigation of ice properties, characterising the dynamic behaviour of hail impact on a rigid aluminium. The initial phase is followed by a study of hail impact on PV modules, including indoor testing and outdoor monitoring of hail-damaged PV modules collected from hail-impacted areas in Locarno.

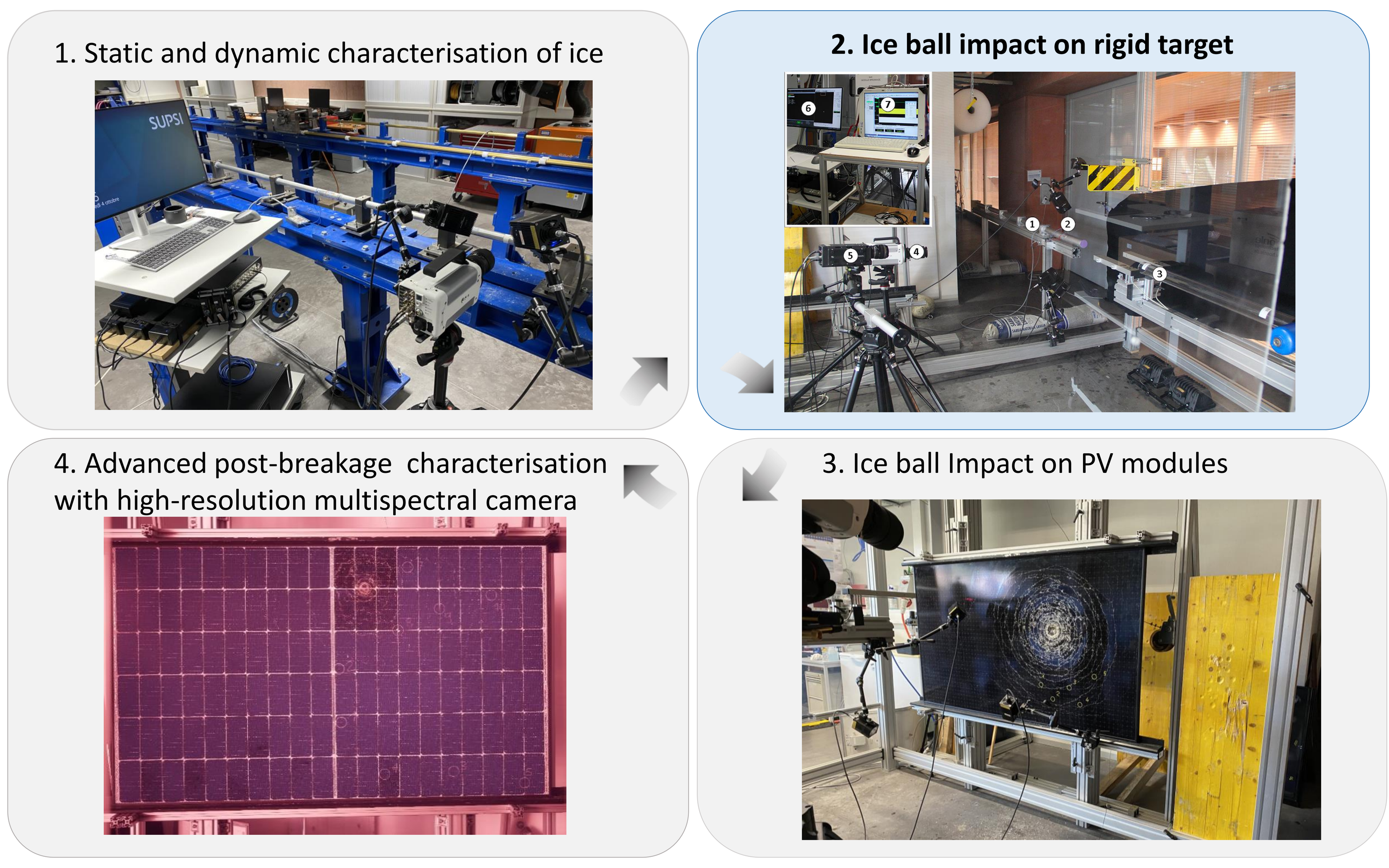


The number of hailstorm days has significantly increased in recent years.

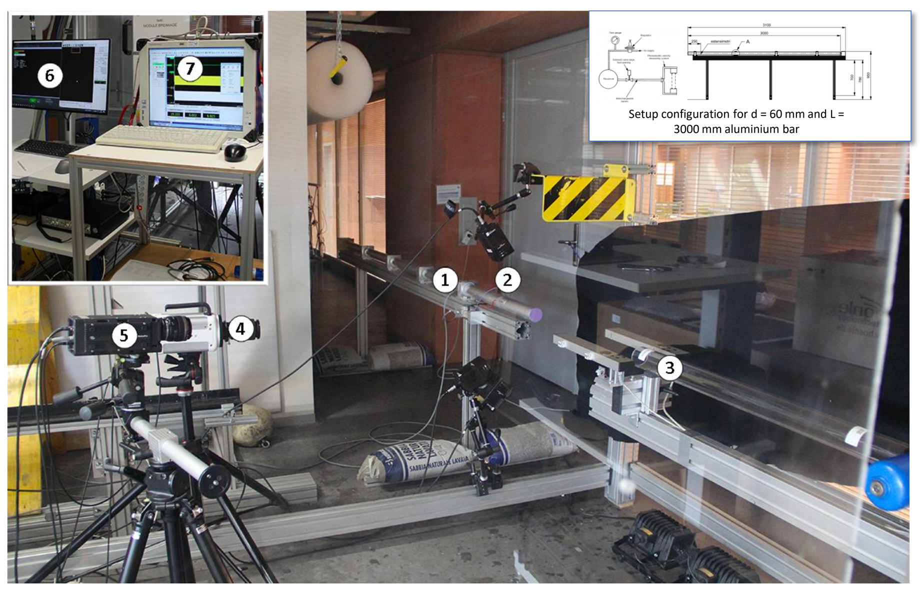
Number of reports and days with large (20 mm), very large (50mm), and giant (10 mm) hail between 2006 and 2024 according to the ESWD. Source: ESSL, European Severe Weather Database: www.eswd.eu

Mechanical characterisation of ice properties

Measurement approach



Setup for impulse recording: Ice balls impact on a rigid aluminium bar



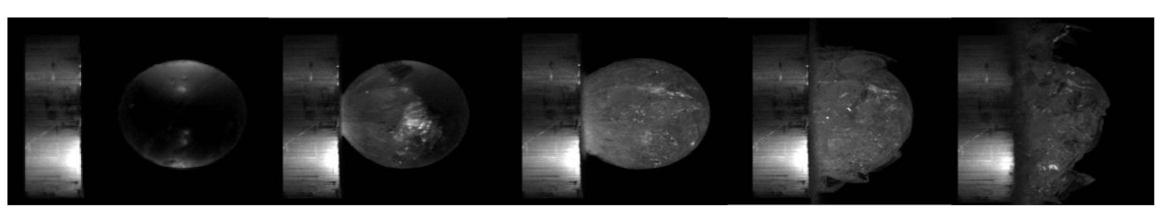
Test variables:

- Ice ball diameters: 30 ÷ 90 mm
- Speed of ice balls: 25 ÷ 140 m/s
- Temperatures: -4°C, -10°C, -20°C, and -28°C
- Impact angle: 0° and 45°

Test setup:

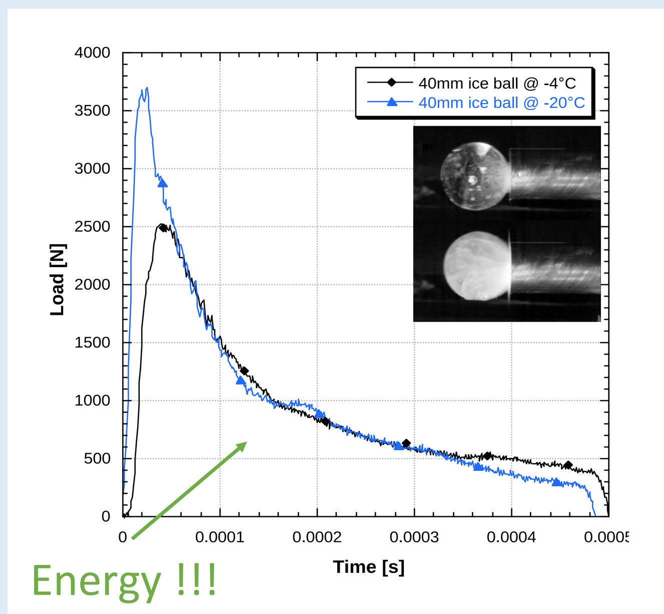
1. Aluminium bar output bar for load-time history signals.
2. Strain-gauge station for strain measurements.
3. Compressed air cannon.
4. Photron NOVA S12 for fast (B/W) image recordings (12'800 fps @ full resolution of 1024x1024).
5. IDT Y4-S3 Camera for fast (Color) image recordings (5'100 fps @ full resolution of 1024x1024).
6. C station for fast camera recording synchronisation.
7. HBM Gen2i acquisition system for data recording @ 1Msample and acquisition time step of $1 \cdot 10^{-6}$ s.

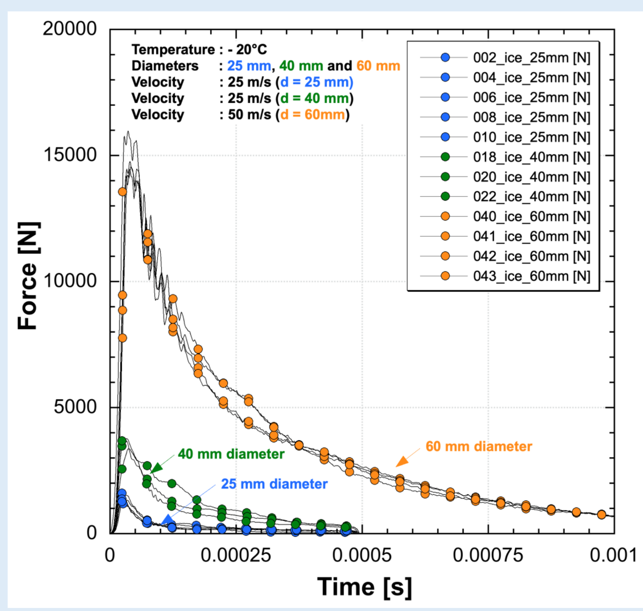
A Hopkinson aluminium bar was used to capture the impulse generated by the impact of an ice ball. The strain signal was recorded using a strain gauge station, and the load signal versus time was subsequently evaluated. Two high-speed cameras were employed to capture the impact of the ice ball on the target.



Ice ball impact on aluminium bar: Illustrated stages of ice ball breakage [d = 40 mm, v = 25 m/s]

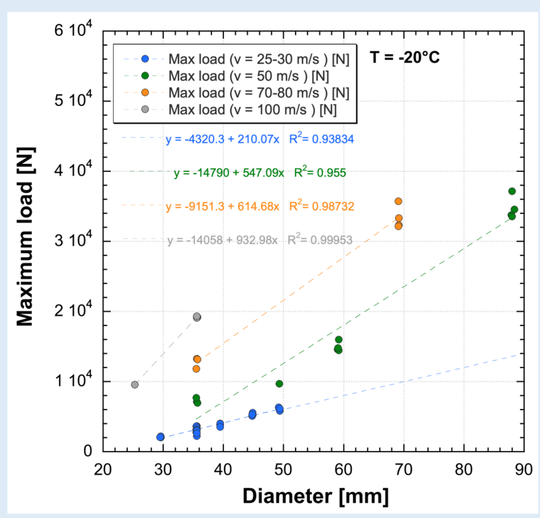
Main findings: Correlation study of ice ball impact on Hopkinson aluminium bar



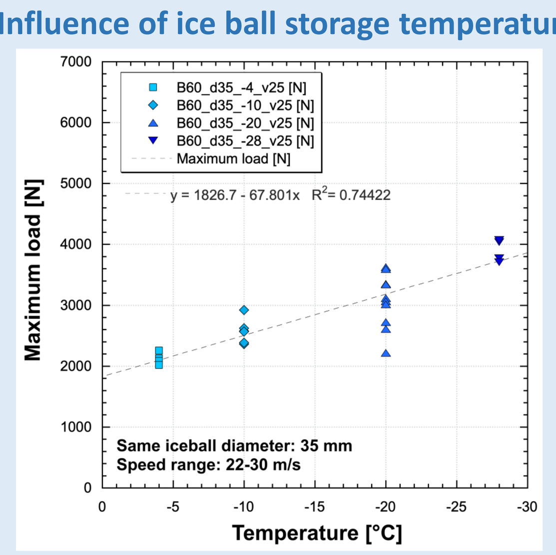


Maximum load increases for increasing ice ball diameters (at similar velocities).

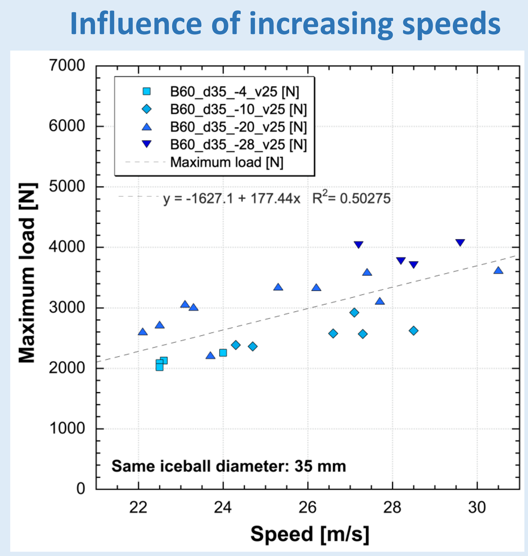
Influence of ice ball diameters



Influence of ice ball storage temperature



Influence of increasing speeds



Validation: How to put all this data into a single equation?

Five physical variables (n) are involved :

$$f(F_P, R, V_0, \sigma_T, c) = 0$$

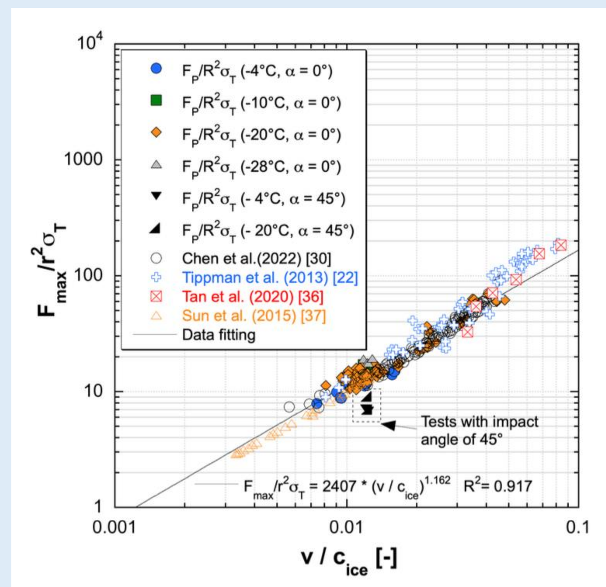
Three fundamental dimensions (k) (length, mass, and time), so based on the Buckingham[1] theorem, **two independent dimensionless parameters (p)** can be constructed:

$$\frac{F_P}{R^2 \cdot \sigma_T} \qquad \frac{F_P}{R^2 \cdot \sigma_T}$$

This led to an empirical equation that can be practically applied to **load estimation**. It is based on the ice ball radius, dynamic ice tensile strength, impact speed, and the elastic wave velocity of ice.

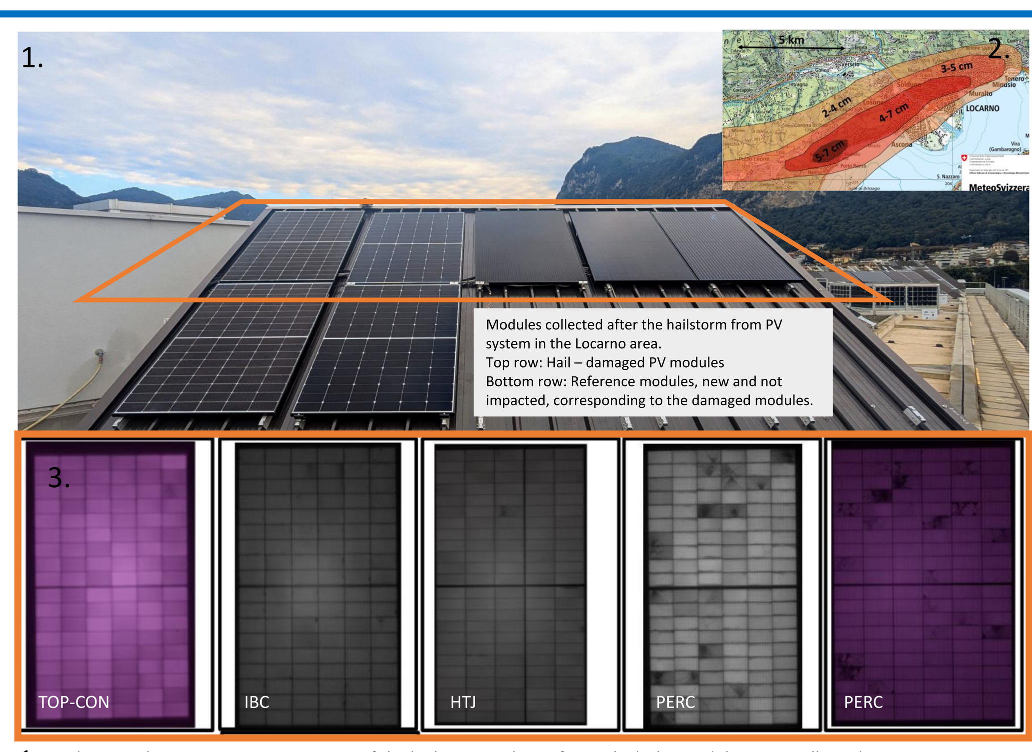
$$F_P = 1257.3 \cdot R^2 \cdot \sigma_T \cdot \left(\frac{V_0}{c} \cdot cos(\alpha)\right)^{1.2311} \qquad \begin{bmatrix} -4^oC \leq T \leq -28^oC \\ 25\,m/s \leq V_0 \leq 100\,m/s \\ 12.5\,mm \leq R \leq 45\,mm \\ \sigma_T = 1.80MPa \end{bmatrix}$$

Coefficients similar to those of Chen et al.[2], were found, calibrated it with a dynamic ice tensile strength value and considering the impact angle.



Summary and Outlook

- Data demonstrate the impact of ice on a rigid target, showing a strong linear correlations for ice ball diameters of 25 mm, 40 mm, and 60 mm (maximum load x ice ball diameter; maximum load x speed).
- Subsequent research step will focus on capturing the impulse data on real PV module surfaces to further evaluate their response to hail impacts.
- Indoor testing and outdoor accelerated aging campaigns are being conducted to assess PV modules affected by actual hailstorms that occurred in the Locarno area, Switzerland in August 2023.
  The outdoor monitoring campaign is starting in September 2024, will continue over the next two years.
  The setup is installed on corrugated rooftops to replicate real rooftop conditions and is being accelerated by limiting backside ventilation and applying shadow masks. Four different solar module technologies are under investigation.



1. Outdoor accelerate aging setup; . 2. Map of the hail-impacted area from which the modules were collected
3. EL imaging of hail impacted modules post hailstorm, installed for outdoor monitoring. Glass thickness - 3.2 mm for each of the module, fully tempered glass.

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