Contents lists available at ScienceDirect

### Materials Letters

journal homepage: www.elsevier.com/locate/matlet

# Advanced characterisation of photovoltaics for hail resistance

## Ezio Cadoni<sup>a,\*</sup>, Daniele Forni<sup>a</sup>, Matteo Dotta<sup>a</sup>, Giovanni Bellenda<sup>b</sup>, Mauro Caccivio<sup>b</sup>

<sup>a</sup> University of Applied Sciences and Arts of Southern Switzerland – DynaMat SUPSI Laboratory, Via Flora Ruchat-Roncati, 15, Mendrisio 6850, Switzerland <sup>b</sup> University of Applied Sciences and Arts of Southern Switzerland – SUPSI PVLab, Via Flora Ruchat-Roncati 15, Mendrisio 6850, Switzerland

### ARTICLE INFO

Keywords: Hail stone Photovoltaic panel Hopkinson bar Impact Safety

### ABSTRACT

Climate change is intensifying severe weather events, especially in alpine environments where hailstorms are more frequent and intense. In particular, hail damage seriously affects photovoltaic systems. The severity of hailstorms as well as impact responses are important factors in mitigating loss, so the first research area that needs to be addressed is the resistance of photovoltaic modules to hail. According to IEC 61215 standard, a PV module should resist at the minimum to the impact of a hailstore of 25 mm launched at 80 km/h, while the Swiss VKF standard demands a minimum of 30 mm, practically making it 40 mm or more. The hail test stand is being enhanced to support larger diameters and higher speed, enabling module manufacturers to assess their products with adequate safety margins. Larger ice ball requires evaluating sample preparation, repeatability, representativity, and the ability to handle high speeds and masses in order to minimise uncertainty in impact energy. In this preliminary study, ice ball samples with diameters of 25, 40, and 70 mm were tested on a Hopkinson bar at speeds from 20 to 140 m/s and temperatures from -5 °C to -20 °C. The effects of impact velocity, loading rate, and impact time were examined. Finally, the first tests on PV modulus with large ice ball and high velocity are presented.

### 1. Introduction

Extreme weather events are increasing due to climate change [1], even more so in alpine environments, where hailstorms are more frequent and intense. The Alpine zone has been greatly affected by great storms. The hail diameters have recently risen to 100 mm, causing damage of 100 million CHF in Switzerland alone in 2021. Europe experienced a large number of severe hailstorms in 2021, according to the European Severe Weather Database [2]. There have been 5195 reports of large hail (>2 cm), 871 reports of very large hail (>5 cm), and 29 reports of giant hail (>10 cm).

Photovoltaics are particularly vulnerable to hail damage: their widespread adoption to meet the  $CO_2$  reduction goals set by COP26 is one of the key instruments for reducing global warming. As a consequence, the development of new standards is proceeding quickly alongside technological advancements: the resistance to hail impact is no exception, and an IEC working group has been formed for the specification of a new international technical specification (IEC TS 63397) on the topic.

A hail test is traditionally used to qualify a PV module at IEC level (IEC 61215-2, MQT17) and is defined as 25 mm diameter and 80 km/h  $\,$ 

speed. Swiss standards, issued by the VKF (Vereinigung Kantonaler Feuerversicherungen, association of cantonal fire insurers), are more demanding because of the particular conditions of the environment. They set a minimum requirement of 30 mm, but in practice, they increase it to 40 mm. For the purpose of ensuring adequate test margins for module manufacturers to evaluate the robustness of their products, SUPSI PVLab, the only accredited laboratory in Switzerland for PV modules based on ISO 17025, is developing improvements to the hail test stand to reach 100 mm in diameter and 166 km/h in speed. Additionally, the increase in ice ball diameter necessitates the evaluation of sample preparation, repeatability, and representativeness, as well as the ability to handle high speeds with high masses to reduce uncertainty in impact energy, as required by the Swiss standards.

In this frame, a new research project named ACHILLES"Advanced CHaracterisatIon of photovoLtaics for haiL rESistance", funded by VKF, is in progress with University of Applied Sciences and Arts of Southern Switzerland (involving SUPSI PVlab and DynaMat SUPSI Laboratory), Eastern Switzerland University of Applied Sciences (OST – Institute für Solar Technik), and Swissolar as partners.

https://doi.org/10.1016/j.matlet.2023.135371

Received 29 June 2023; Received in revised form 25 August 2023; Accepted 7 October 2023 Available online 11 October 2023 0167-577X/© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).







<sup>\*</sup> Corresponding author at: University of Applied Sciences and Arts of Southern Switzerland, 6850 Mendrisio, Switzerland. *E-mail address:* ezio.cadoni@supsi.ch (E. Cadoni).



Fig. 1. Setup for impulse recording (load vs time) of ice balls on a rigid aluminium bar (a) and for ice ball impact on a the PV panel (b).

 Table 1

 Experimental results with hail stones of different diameter.

Diameter (mm)	Temperature (°C)	Mass (g)	Velocity (m/s)	Max. load (N)	Fracture time (µs)
$25.1 \pm 0.1$	$-5^{\circ}C$	7.9 ± 0.1	$\begin{array}{c} 21.8 \pm \\ 0.8 \end{array}$	$\begin{array}{c} 851 \pm \\ 112 \end{array}$	$37\pm7$
$25.3 \pm 0.1$	-20 °C	8.0 ± 0.1	$23.6 \pm 0.5$	$1447 \pm 144$	$26\pm 4$
$\textbf{39.4} \pm \textbf{0.1}$	$-5^{\circ}C$	29.7 ±	27.7 ±	2257 ± 72	$43\pm10$
$39.5\pm0.0$	-20 °C	29.8 ±	27.8 ±	3594 ±	$34\pm2$
$69.0 \pm 0.1$	$-5^{\circ}C$	159.7 + 0.2	36.7 ±	10042 + 417	$48\pm1$
$69.1 \pm 0.1$	−20 °C	$160.0 \pm 0.1$	38.5 ± 0.1	$14463 \pm 586$	$47\pm4$

#### 2. Experimental set up

A panel's degree of damage is largely determined by the force history generated during the impact between the hail stone and the PV panel. This task can be quite challenging due to the difficulties of direct measurement of the force history. This problem has been studied experimentally as well as numerically by several researchers (e.g. [3–6]). The main purpose of this preliminary tests is to examine the effects of hail stones on photovoltaic (PV) panels and quantify the impact caused by

hail. In the initial phase of the research, a Hopkinson bar was employed to capture the waveform resulting from the collision of the ice projectiles with the instrumented aluminium bar. The setup shown in Fig. 1a consists of an aluminium bar (1) with diameter of 30 mm and 1.5 m in length; strain-gauge station (2); a gas gun (3) for ice ball acceleration; Photron NOVA S12 fast camera (4) for fast (B/W) image recordings (12800 fps at full resolution of  $1024 \times 1024$  pixels). A PC station for fast camera recording synchronisation and an acquisition system (HBM Gen2i) for data recording at 1Msample and acquisition time step of  $1 \cdot 10^{-6}$  s.

With reference to Fig. 1b, in order to study the effect of the ice ball impact on PV panel the gas gun (5) is positioned in front of the PV panel and the impact was recorded by Photron NOVA S12 fast camera 06 and IDT Y4-S3 fast camera (7) (5100 fps at full resolution of  $1024 \times 1024$  pixels) obtaining the cracking process during the PV panel failure.

Spherical ice specimens of nominal diameters of 25, 40, and 70 mm were prepared by using industrial ice. A gas gun was used in order to accelerate the spherical ice specimens in order to achieve the target speed. A round plexiglass tube with different inner diameters was used to guide the spherical ice inside of it. To measure the velocity of the spherical ice specimens, a laser sensor was placed at the end of the tube.

#### 3. Preliminary experimental results

As part of the initial testing, three different diameters (25, 40 and 70 mm) of spheroid specimens were shot onto the Hopkinson bar at the



Fig. 2. Load versus time curves: a) specimens with 70 mm in diameter at -5 °C and -20 °C; comparison between 40 mm and 25 mm diameter specimens at -20 °C.



Fig. 3. Images of the spherical ice specimens' impact on the Hopkinson bar (a-n) and on PV panel (o-s) (12800 fps).

same velocity and at two different frozen temperatures, -5 °C and -20 °C, to compare loading versus time response. Table 1 summarises the average results under different conditions. Specifically, the specimen temperature and mass were reported, as well as the diameter of the specimen. In addition to the results regarding velocity, maximum load registered on the Hopkinson bar, and time when it occurred. In general, monotonically increasing trends can be observed for individual test groups. However, there appears to be some dispersion in the overall data. The lower temperature (-20 °C) causes an increase in peak load and a reduction in fracture time.

By comparing the average values of samples having 40 mm diameters, the temperature decrease causes a double loading rate, resulting in a higher stress rate on the bar, i.e. at -5 °C the stress rate is around 74 GPa/s and at -20 °C about 150 GPa/s. In the case of 25, 40, and 70 mm ice balls at -20 °C, peak forces are approximately 70 %, 59 %, and 44 % higher than those at -5 °C at the same velocities. For 25, 40, and 70 mm, ice reaches its peak force in a shorter amount of time at -20 °C, which is 30 %, 21 % and 2 % lower than at -5 °C. Fig. 2a shows the comparison between the load versus time curves of 70 mm diameter samples at two temperatures. Decreasing the sample temperature will cause an increase in the peak force, and a reduction in the time it takes for the peak force to be reached. A slightly steeper curve is also visible before the peak for ice frozen at -20 °C. Fig. 2b provides the comparison between the load versus time curves at  $-20\ ^\circ C$  for 25 and 40 mm specimens. Fig. 3 shows photos taken during the impact of three diameters of ice balls. Taking a look at the last sequence, it shows the impact of the ice ball on the PV panel, which highlights the cracking that occurs as a result.

#### 4. Conclusions

Ice balls with three different diameters were launched onto a Hopkinson bar at two different temperatures (-5 °C and -20 °C) to record load versus time history. The results show that ice impact force history is significantly influenced by ice ball size and impact velocity. In proportion to the increase in size and impact velocity, both the peak force and the time corresponding to the peak force increase. Ice ball temperature also plays an important role. A lower temperature leads to a higher peak force and a shorter peak time.

During the first tests on PV panels, the system was exposed to a direct impact from hail stones. Using these preliminary results, the project will move forward with its future tasks, including the analysis of hail stone damage using a multispectral camera, the analysis of PV panels of different ages, ice mechanical characterisation in the same strain rate range, and FEM modelling of phenomena.

#### CRediT authorship contribution statement

**Ezio Cadoni:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Daniele Forni:** Conceptualization, Investigation, Visualization. **Matteo Dotta:** Methodology. **Giovanni Bellenda:** Methodology. **Mauro Caccivio:** Conceptualization, Investigation, Project administration, Funding acquisition.

#### **Declaration of Competing Interest**

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ezio Cadoni reports financial support was provided by University of Applied Sciences and Arts of Southern Switzerland.

#### Data availability

Data will be made available on request.

#### Acknowledgements

A special acknowledgement goes to the University of Applied Sciences and Arts of Southern Switzerland and Vereinigung Kantonaler Feuerversicherungen for the financial support of the "Advanced CHaracterisatIon of photo- voLtaics for haiL rESistance" project.

#### References

 W. Botzen, L. Bouwer, J. van den Bergh, Climate change and hailstorm damage: Empirical evidence and implications for agriculture and insurance, Resour. Energy Econ. 32 (2010) 341–362.

- [2] T. Pucik, Hailstorms of 2021, https://www.essl.org/cms/hailstorms-of-2021/, 2021.
- [3] J. Sun, N. Lam, L. Zhang, D. Ruan, E. Gad, Contact forces generated by hailstone impact, Int. J. Impact Eng 84 (2015) 145–158.
- [4] C. Hammetter, R. Jones, H. Stauffacher, T. Schoenherr, Measurement and modeling of supersonic hailstone impacts, Int. J. Impact Eng. 99 (2017) 48–57.
- [5] S. Chen, E. Gad, L. Zhang, N. Lam, S. Xu, G. Lu, Experiments on an ice ball impacting onto a rigid target, Int. J. Impact Eng. 167 (2022), 104281.
- [6] J.D. Tippmann, H. Kim, J.D. Rhymer, Experimentally validated strain rate dependent material model for spherical ice impact simulation, Int. J. Impact Eng. 57 (2013) 43–54.