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High Fidelity Modeling of Hail Impact on Metal Roofs

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Abstract

The number of reported hail events has increased over the past several years. Hail storms pose substantial risks to property and an array of challenges to various stakeholders, including insurance companies who work to quantify risk, manufacturers of roofing and siding products, and owners and design teams making decisions on the serviceability of exterior materials. Current methods for studying hail impact on building materials involve physical testing with ice projectiles intended to simulate hail. This paper introduces an analytical model that can simulate hail impact. The analytical modeling platform allows for the study of boundless parameters, systems and materials, while mitigating the often labor-intensive costs and material waste associated with physical testing. In addition, the use of a material model is expected to lead to more realistic results than the steel and ice impactors used in standard tests.

A non-linear, strain-rate-dependent model has been developed to represent the mechanical response of hail at high strain rates and has been calibrated and validated against experimental data. For this study, metal roofing was selected as the material to be impacted. A non-linear ductile fracture model was used to represent the behavior of representative steel roof systems. Results from this benchmark problem prove to be in agreement with widely accepted experimental results. Additional parametric studies investigated the hail impact on 26-gauge standing-seam and R-panel joints. The study shows that the novel modeling approach can be used to predict hail impact response of building materials, which poses certain advantages over physical testing and current methods. The developed model provides a well-founded methodology that can be used to quantify the risk of hailstorms damaging roof systems, and to improve and optimize future designs.

1. Introduction

The annual property loss and risk related to hail in the US is measured in billions [1]. Like other weather phenomena, forecasting hail is limited to the short-term and future risk is based on historic data.

Additionally, hail storm intensity can vary over short distances, and the occurrence of hail at a given site still requires field verification. These circumstances, along with an ever-changing roof and building material industry, contribute to a multitude of conditions and scenarios related to hail impact (e.g., hail-related 'openings' in an R-panel roof). Without a robust understanding of the vulnerability of different materials, shaping, and detailing, risk quantification models may be inaccurate, and insurance underwriters may lack an understanding of specific conditions resulting from impact on a particular system or material.

On the other hand, manufacturers develop and promote new products to be more "hail-resistant", and issue product warranties. In the absence of analytical models, the only way to understand hail impact consequences is to conduct physical testing, which is both expensive and impossible to scale. In this study, we present a high fidelity non-linear modeling approach that can accurately predict the response of metal roofs subjected to hail impact. While the discussion and examples herein are focused on metal roofs, the approach can be readily adapted to evaluate other materials including different types of metal roof and wall systems, asphalt composite shingles, and membrane roofing systems.

2. Characterization and Modeling of Hail

Hail, or ice, is a very strain rate dependent material, as shown in Figure 1. At extremely low strain rates (~1e-6 s^{-1}), ice behaves pretty much as a fluid or a largely viscoelastic solid [2]. At medium strain rates (~1e-2 s^{-1} to 1 s^{-1}), ice experiences a ductile to brittle transition where it begins to develop structural strengths. At high (impact) strain rates (~10 s^{-1} to 1000 s^{-1}), ice turns into a brittle material that exhibits significant compressive strength reaching 3.0ksi (20MPa) [3]. Therefore, accurate representation of hail requires a model capable of simulating the rate-dependent response of ice, as well as the various fracture-related phenomena occurring at each strain rate.

We developed a material model for ice that is capable of capturing fracturing behavior at impact strain rates. It is based on a three-invariant, visco-plastic model, which iswidely used to represent granular materials such as soil and concrete [4]. This class of model was selected because it can represent the dominant features of hail response, including pressure dependence (stronger in compression than in tension), rate dependence, and fracture. The model parameters, (e.g., strength, ductility and rate-dependence) have been calibrated from the experimental data published in [3]. The calibrated model was validated against another experimental study [5] that utilized hail specimens with a diameter ranging between 2.0 to 2.5 inches, which are comparable to those commonly seen in hailstorms,. The study used in the validation consisted of an experimental setup composed of a mass-spring system that is impacted by an ice projectile. As shown in Figure 2, forces are recorded via two mechanisms:

- Spring forces via monitoring spring extension using a high speed camera
- Contact forces via accelerometer recordings of the rigid mass

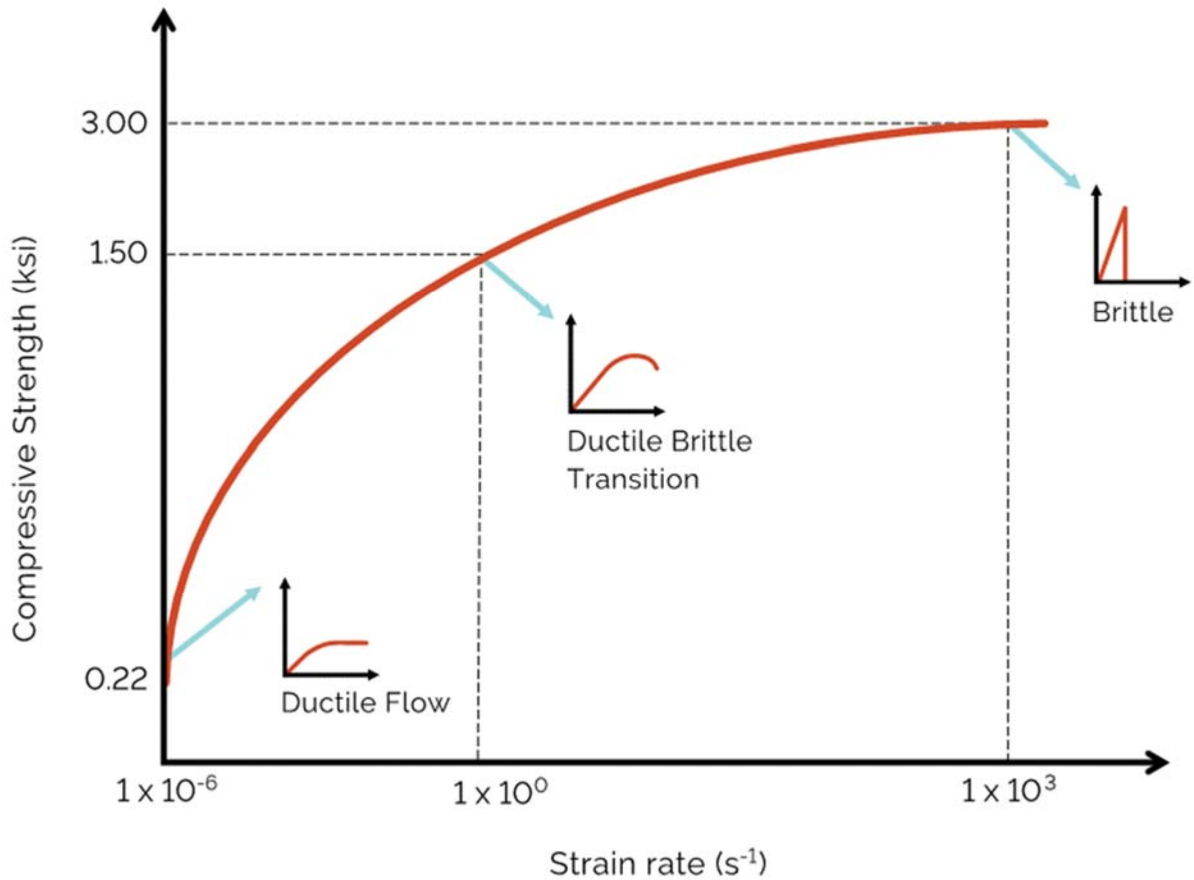

Figure 1: Rate dependence of ice mechanical response

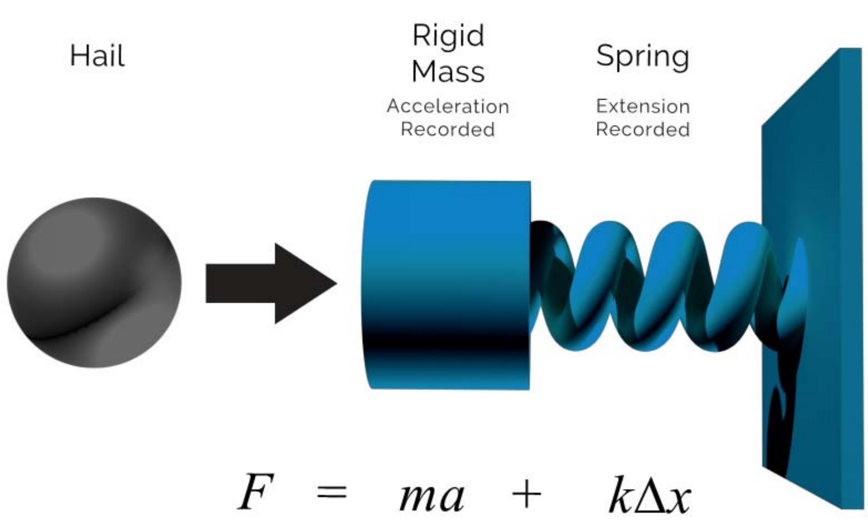

Figure 2: Validation experiment setup.

A Finite Element (FE) analysis model was developed to resemble the setup in Figure 2. The material model developed and calibrated to represent hail response was used to describe the hail material. Figures 3 and 4 show a comparison between forces recorded from experiments vs. calculated from the FE model. The detailed study leading to Figures 3 and 4 point to the following observations:

- Accurate representation of hail strength, ductility (amount of strain to fracture) is essential to precise matching of force amplitudes in Figure 3.
- Accurate representation of hail rate dependent response is key to calculation of contact forces in Figure 4, which are consequential in terms of local damage and failure of structural elements.

The calibration and validation study proves the applicability of the developed non-linear model to representing hail/ice response at elevated strain rates.

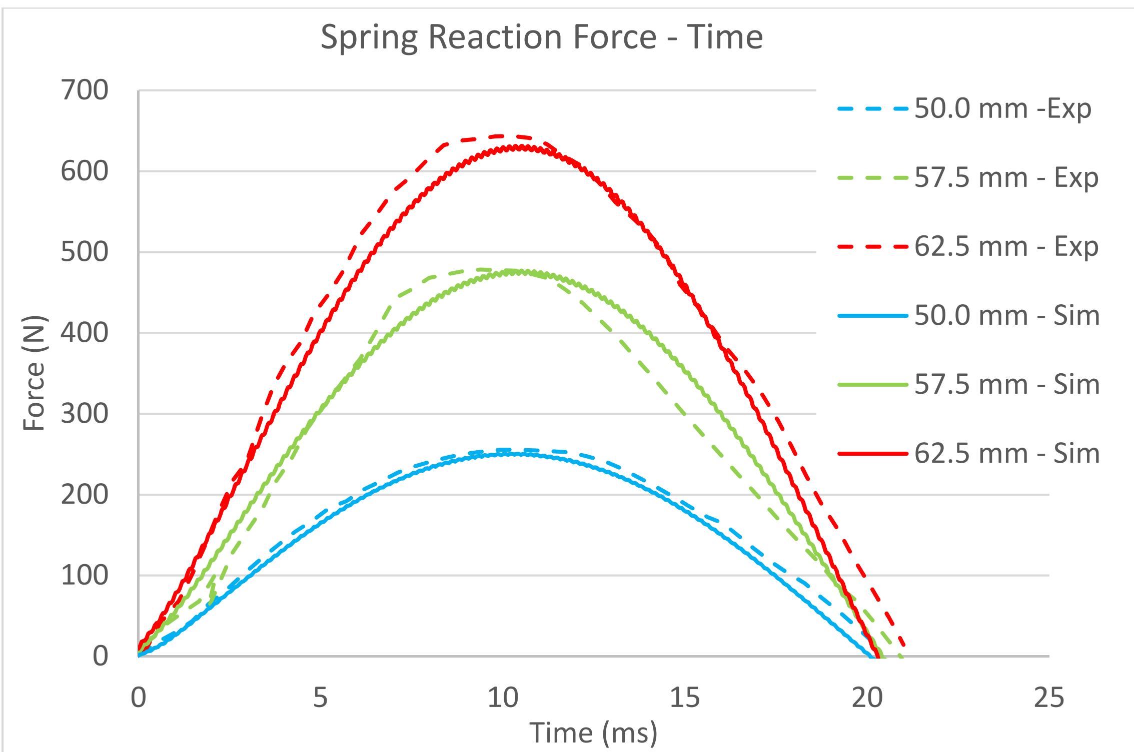

Figure 3: Spring reaction forces vs. time. Comparison of experimental (solid) vs. simulated (dashed) data for different hail sizes

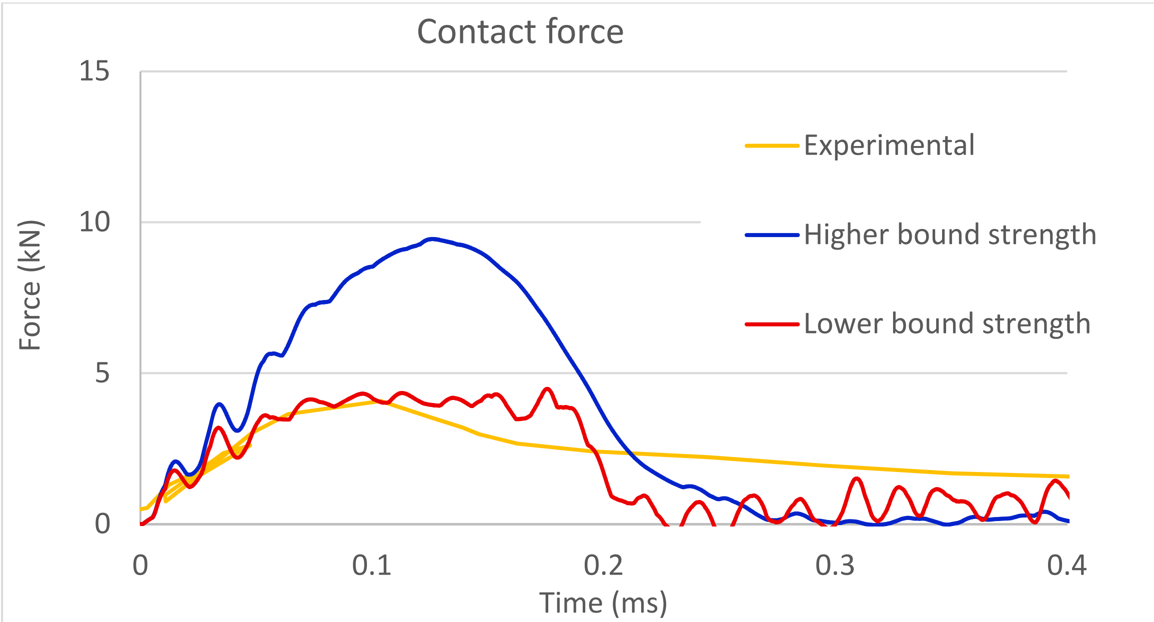

Figure 4: Contact (accelerometer) forces vs. time. Experimental in yellow, higher and lower bound strength simulated models in blue and red, respectively.

3. Application to Hail Impact on Metal Roofs

An FE model was created to simulate hail impact on the mid-panel of an unsupported standing seam roof. Hail density and velocity were based on the study in [6] and are plotted in Figures 6 and 7.

Different variations of hail material properties were investigated, including shape, strength (rate fit) and density. This was done in an attempt to bound the uncertainty associated with hail properties. The hail was modeled at 1.5 in, 3.0 in and 4.5 in, reflect thesizes that most frequently lead to damage. Figure 5 shows the distribution of hail observed in various hailstorms as published in [7]. In reality, hail comes in various shapes; some are almost perfectly spherical while others have pointed edges that may lead to more significant local stresses and damage. In this study, we modeled hail as a perfect sphere as well as a cone with a filleted bottom tip.

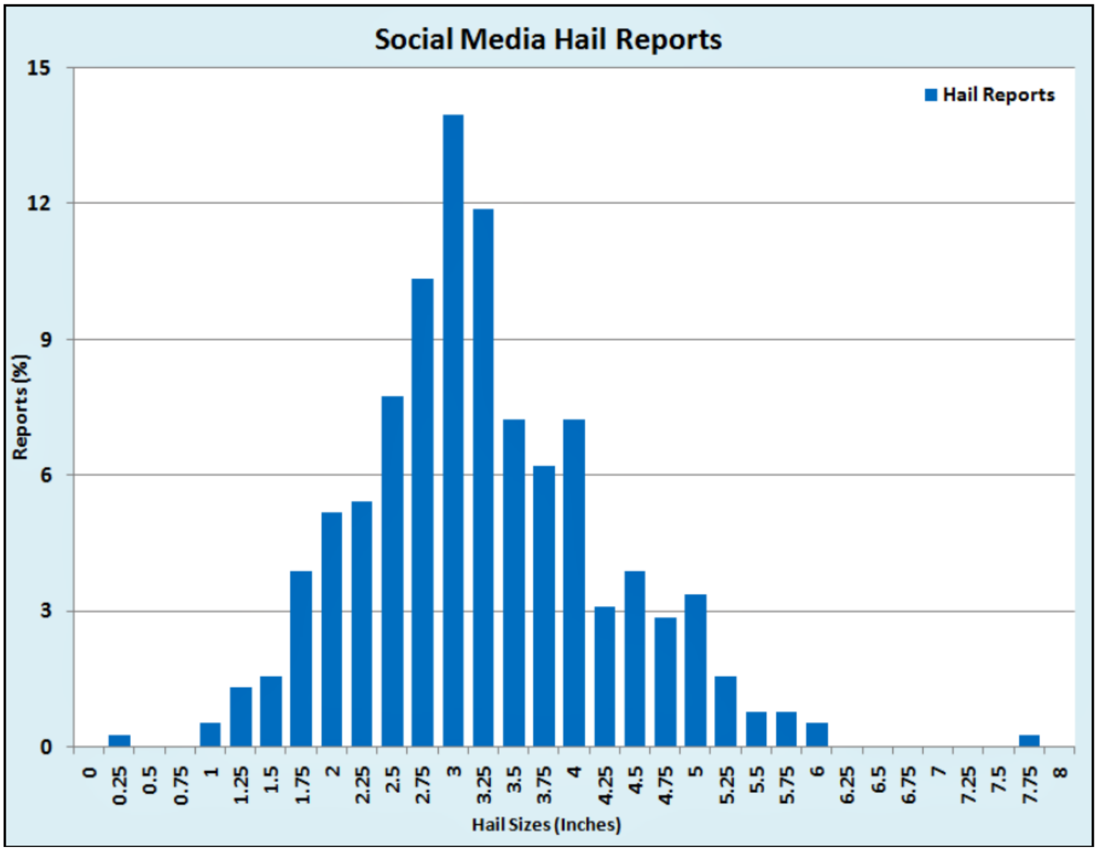

Figure 5 – Hail size distribution as observed from various hail storms - the histogram is copied as published in [7]

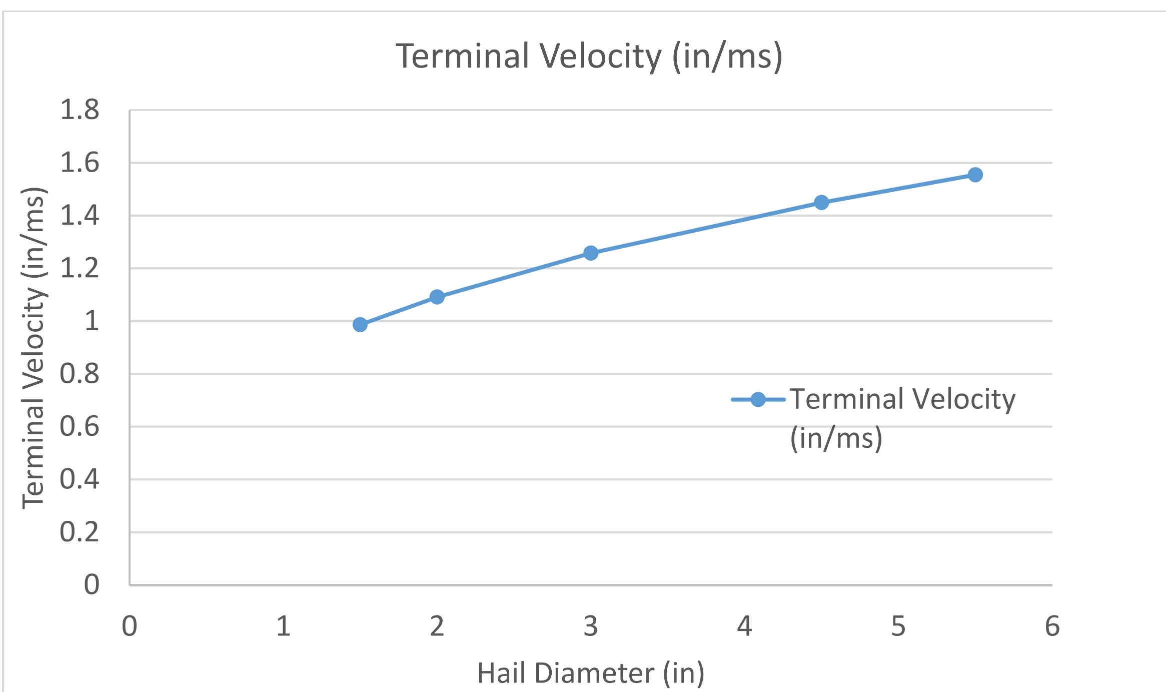

Figure 6 – Terminal velocity vs. Hail diameter based on the data published in [6]

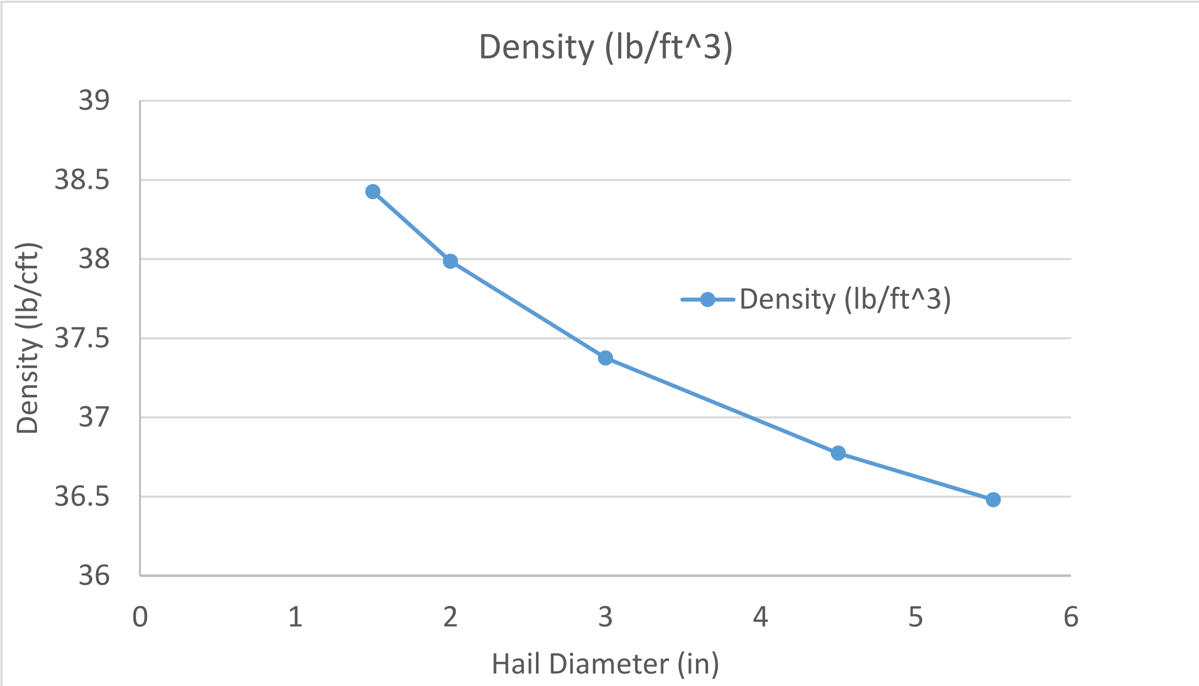

Figure 7 – Hail density vs. Diameter based on the data published in [6]

Figures 8 and 9 below show deformed shapes due to the impact of spherical and conical 4.5 inch hail, respectively. Figure 10 shows how the results compare against widely accepted experimental studies [8]. From the analysis of results in Figures 8-12, the following may be concluded:

- The developed analysis model yields predictions that align with the currently accepted understanding of typical hail impact damage.
- Hail of higher strength and density leads to larger indentations.
- Pointed hail leads to more significant indentations; and if large enough, may cause metal fracture.

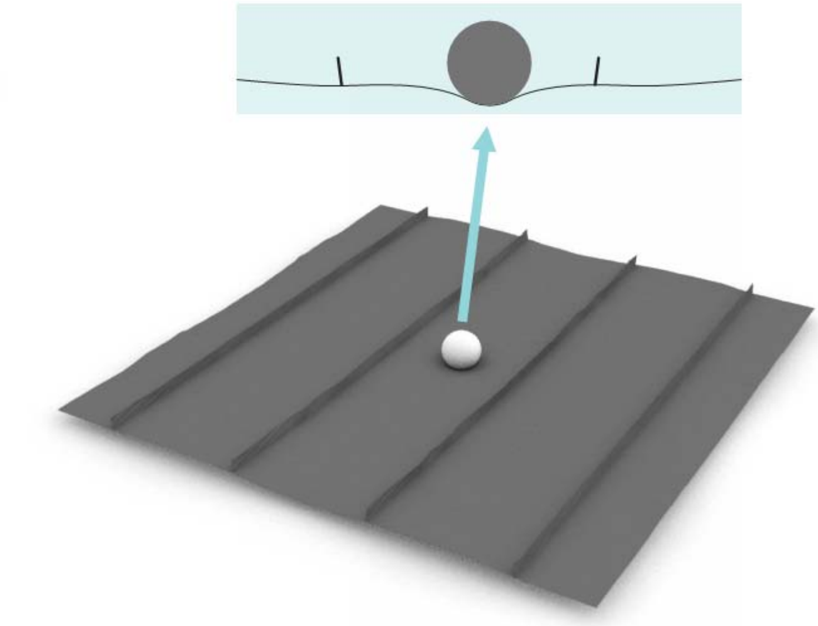

Figure 8: Deformed shape below 4.5 in hail sphere

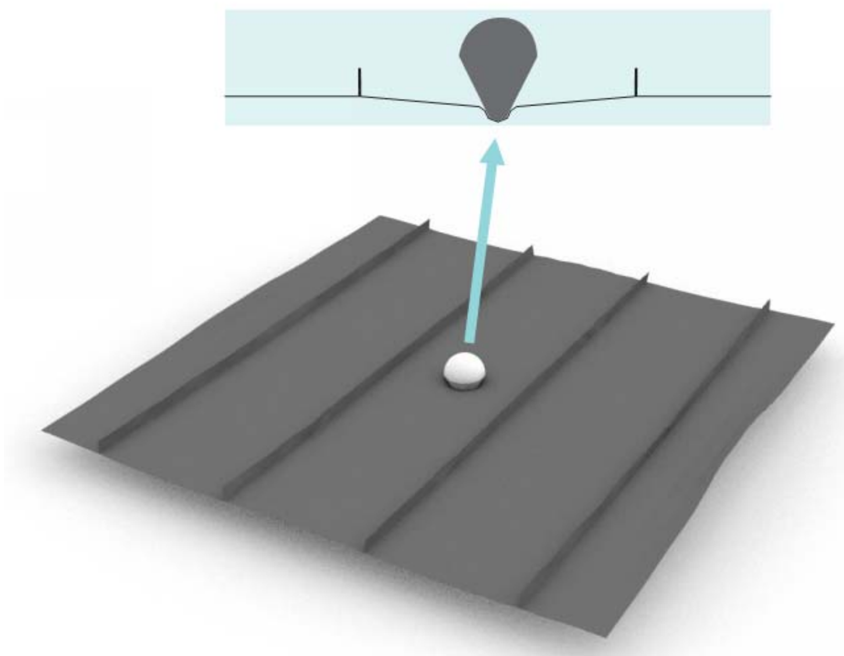

Figure 9: Deformed shape below 4.5 in hail cone

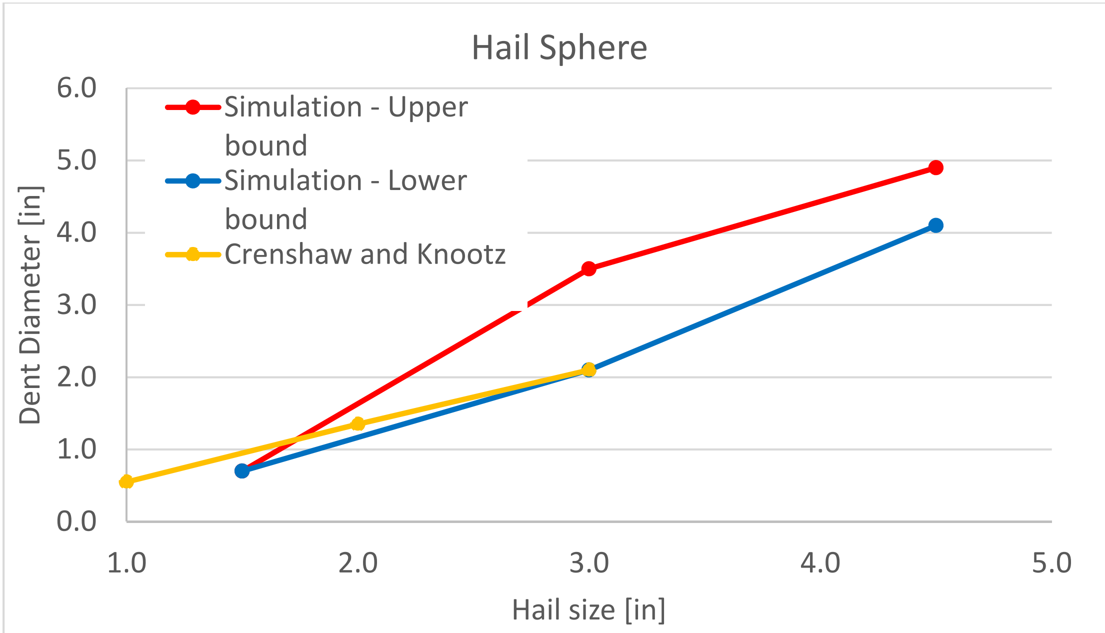

Figure 10: Dent diameter vs. hail size comparison between simulation (upper and lower bounds) and experimental data from Crenshaw and Knootz [8]

In order to develop a better understanding of the effect of hail impact on roof connections, an FE model was developed to simulate a double-lock seam. Various hail sizes, properties and impact angles were investigated. Figures 11 and 12 show the deformed shape of the double-lock seam in response to hail impact for unsupported and plywood-supported conditions, respectively. In the unsupported conditions, the seam experiences local buckling and the panel shows large permanent strains due to local bending. In the supported condition, the plywood limits the deformations of the panel and damage is limited to local seam buckling. The insights gained from this modeling and analysis approach may be used to evaluate the resistance of current roof systems to hail and to improve future designs.

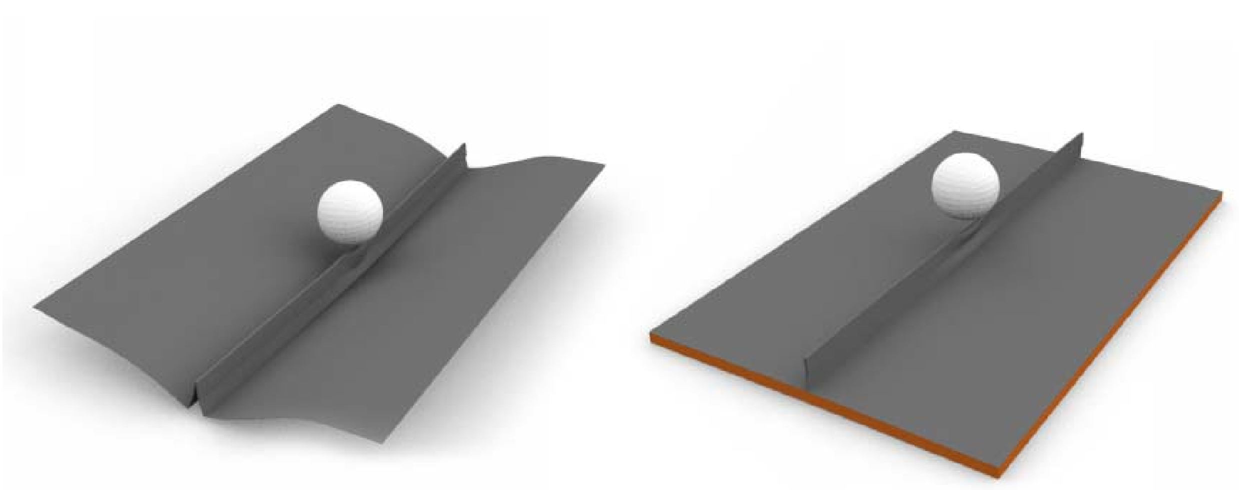

Figure 11: Simulated double-lock standing seam deformation due to hail impact

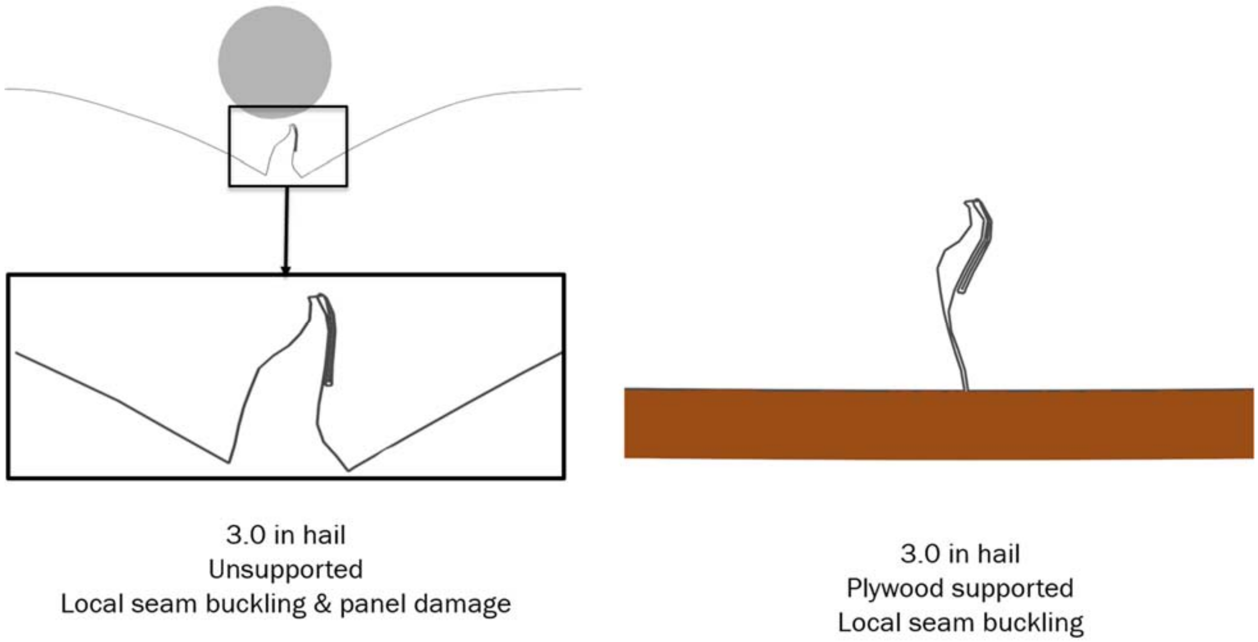

Figure 12: Section through double-lock standing seam deformed due to hail impact

4. Summary

The study presented here introduces a novel, non-linear material model that can represent hail response to impact at elevated strain rates. The model was calibrated and validated against experimental data. The developed model was used within an FE framework to showcase the capability of the analysis approach to simulate hail impact on metal roofs. The results from the analysis model match experimental data from different studies, which proves the reliability of the model to represent hail impact scenarios.

The developed analysis methodology provides profound basis for prediction of extent of damage due to hailstorms, which can benefit risk and insurance calculations. In addition, the model can be used to assess the performance of current roof systems and optimize future designs. The use of the developed analytical model reduces the need for extensive experimental testing required for the assessment, qualification and certification of roofing systems.

References

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