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Numerical and Experimental Investigation of Hail Impact-Induced Dent Depth on Steel Sheets

Meryem Dilara Kop[1], Mehmet Eren Uz[2], Yuze Nian[3], Mehmet Avcar[4*]

[1] Graduate School of Natural and Applied Sciences, Suleyman Demirel University, 32260 Isparta, Türkiye
[2] Department of Civil Engineering, Faculty of Engineering, Aydin Adnan Menderes University, 09100 Aydin, Türkiye
[3] School of Civil Engineering and Architecture, Jiangsu University of Science and Technology, 212100 Zhenjiang, China
[4] Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Suleyman Demirel University, 32260 Isparta, Türkiye

[*] Correspondence: Mehmet Avcar (mehmetavcar@sdu.edu.tr)

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Abstract: The impact of artificial hailstones on G300 steel sheets with varying thicknesses has been systematically investigated to evaluate the resulting dent depths. Two distinct methods for producing simulated hailstones were employed: one utilizing polyvinyl alcohol (PVA) adhesive and the other incorporating liquid nitrogen. Comparative analyses of these techniques revealed that the liquid nitrogen method, in conjunction with demineralized water, yielded more accurate results than the PVA adhesive-based method. Experimental findings were cross-referenced with theoretical predictions and finite element simulations, with model accuracy being validated against existing research in the field. The study focused on three hailstone diameters—38mm, 45mm, and 50mm—across various sheet thicknesses. Results indicate that dent depth is primarily influenced by the impact energy, sheet metal thickness, and hailstone diameter. Notably, the momentum of the hailstone plays a critical role, with smaller, higher-momentum hailstones inducing permanent deformations comparable to those of larger, lower-momentum hailstones, even when the impact energies are equivalent. The findings suggest that variations in hailstone momentum can lead to similar deformation patterns across different sizes, emphasizing the importance of momentum in the design of steel sheet materials for enhanced hailstone impact resistance. This study contributes valuable insights for the development of more resilient materials in industries subject to dynamic impact loading, such as automotive and aerospace engineering.

Keywords: Dynamic impact test; Finite element model; Simulated hailstone; Dent depth; Steel sheet

1 Introduction

Hailstorms are a type of natural disaster that can have a significant effect on materials such as vehicles and roofing. The extent of damage changes depending on the frequency of the hailstorms and the size of hailstones [1]. Predictions about the frequency and size of hailstones tend to increase because of climate change. These augmentations give greater substance to the investigation of roof coverings under hail damage. Different materials are nowadays used for roof coverings. However, the advantages of metal roofing make it widely utilized. Several materials and methods have been used in impact tests. One of the initial studies was conducted with natural hailstones by Niemeier and Burley [2]. Steel or other indentors were also used to simulate hailstones by Nomura et al. [3], Vreede [4], and Shi et al. [5] in the impact tests. To increase the strength of the ice ball, Swift [6] used cotton inside it. Cotton and demineralized water mixtures were not integrated well with higher velocities. Therefore, Uz et al. [7] and Wu [8] used the 12% PVA and 88% demineralized water method in impact tests. Four essential qualities of natural hailstones exist. These are integrity, density, crystal structure, and onion-layered structure [9]. The PVA addition method shows a good fit with real hailstone based on the hailstone's density and integrity following impact. However, the crystal structure and onion-layered structure of natural hailstone cannot be simulated using this method. Due to the fact that there were nuclei at the center of the hailstone [10], Yilmaz et al. [9] used liquid nitrogen and demineralized water to simulate natural hailstone. According to the research results [7, 9, 11–13], artificial hailstones created using this technique exhibited every attribute of natural hailstones.

Currently, there isn't a very reliable way to predict how big a dent will be from a hailstone hitting a surface. This prediction depends on factors like the material's strength, thickness, stiffness, shape of the roof, the weight of the hailstone, and how fast it hits. The existing roof profiles are not optimized for hailstone impact resistance in the finite element models. The main feature of this study is how accurately the artificial hailstone was created in finite element models to resemble real hailstones, and how closely the results matched real-life tests regarding dent size and depth.

A review of the literature above indicates that there is uncertainty regarding the relationships between the material yield stress and the dent resistance, as well as between the sheet thickness and the dent resistance. The yield stress and the sheet thickness are central to the development of optimum roofing profiles and cladding systems. The first objective is, therefore, to determine the effects of material yield stress and sheet thickness on the dent resistance of steel sheeting. This objective involves the use of finite element simulation, plate dynamics theory, and laboratory tests. One crucial objective is to establish a theoretical framework for measuring hailstone impact, whether based on kinetic energy, momentum, or some other parameters.

2 Methodology

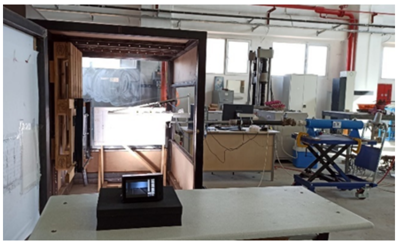


Figure 1. The experimental setup for Hailstone impact

Table 1. Test results for artificial hailstone made of liquid nitrogen and demineralized water

ID	Plate Thickness (mm)	Hail Diameter (mm)	Pressure (bar)	Density of Hailstone (g/cm^3)	Velocity (m/s)		Projectile Integrity
					Sensor	Camera	
1	0.30	46.50	3.20	1007.80	28.50	24.50	Whole
2	0.30	46.90	3.30	938.20	29.30	29.10	Shattered
3	0.30	47.20	3.30	979.00	34.60	29.10	Whole
4	0.30	47.90	3.30	927.40	32.30	28.50	Major Broken
5	0.30	48.90	3.30	955.30	25.10	25.70	Whole
6	0.30	46.10	3.30	949.90	40.00	33.50	Whole
7	0.30	49.40	3.30	924.30	32.70	31.50	Minor Broken
8	0.30	46.60	3.30	963.80	27.80	24.40	Major Broken
9	0.45	48.14	3.20	990.03	20.90	21.00	Major Broken
10	0.45	46.30	3.30	1053.40	26.00	27.90	Whole
11	0.45	48.72	3.30	969.20	37.70	31.90	Minor Broken
12	0.45	46.11	3.30	1006.90	27.40	31.00	Major Broken
13	0.45	47.12	3.20	996.30	24.10	26.50	Minor Broken
14	0.45	47.62	3.20	938.70	46.90	23.20	Whole
15	0.45	49.36	3.30	1005.00	111.40	31.10	Minor Broken
16	0.45	48.07	3.30	975.10	25.00	28.00	Maior Broken
17	0.60	44.92	3.10	1077.60	23.30	27.40	Whole
18	0.60	49.23	3.20	989.80	22.50	25.40	Partly intact
19	0.60	48.03	3.30	1012.20	27.70	28.40	Whole
20	0.60	46.34	3.30	1088.00	24.80	29.10	Major Broken
21	0.60	48.15	3.40	997.60	26.40	29.50	Whole
22	0.60	48.83	3.40	996.50	33.80	31.00	Minor Broken
23	0.70	47.42	3.20	989.00	25.10	28.20	Major Broken
24	0.70	49.62	3.20	978.00	28.90	28.20	Shattered
25	0.70	47.33	3.30	1027.60	34.10	29.20	Shattered
26	0.70	45.23	3.30	1032.90	39.50	36.90	Shattered
27	0.70	47.12	3.20	1017.30	30.80	32.20	Shattered

In this study, pneumatic dynamic impact tests were performed. G300 steel sheets were used for the tests. Only liquid nitrogen, 12% PVA, and 88% demineralized water were used to create artificial hailstones. Hailstones with diameters of 38mm, 45mm, and 50mm were selected. Steel sheets had thicknesses of 0.35mm, 0.45mm, 0.60mm, 0.70mm, and 0.80mm measured. The plate measured one meter by one meter. As shown in Figure 1, test setups include an air compressor, air tank, barrel, gas stopper, and manometer. The air tank holds pressurized air that has been extracted from the air compressor. A manometer is used to measure pressure.

Hailstones are placed inside barrels and fired onto steel sheets using a 12-volt DC gas solenoid valve in pressurized air. The associated hailstone reached its own terminal velocity because of the air tank's pressure being adjusted. The top and bottom edges of the steel sheets were carefully fixed without adding any external stiffness. A digital caliper was used to measure the hailstone dimension from three different angles prior to each test. Their masses were also measured to determine the densities of these hailstones. The barrel has two laser sensors to gauge the hailstones' velocity. As shown in Table 1, the high-speed camera used in this investigation was also used to measure the hailstones' velocity.

2.1 Finite Element Model Validation

Making the hailstone was the primary task of the finite element model. shows the model of a quarter hemispherical hailstone used in this study, which is a solid revolved. A quarter model of the spherical projectile was used along with quarter-symmetry boundary conditions to reduce the computational time. A quarter of the hailstone was divided using the datum points for each calculated diameter hailstone that was created in an inner box, as given in Figure 2. Once the line and cover connected at every point, the hailstone was finished. Material properties are a crucial step in the successful creation of FEM. The study of Tippmann [14] used a rigid plate to examine the impact force of hailstones. For this reason, the FEM validation of the hailstone modelled in this study was firstly evaluated using the findings from the study of Tippmann [14]. The rigid plate and hailstone were modelled with the same diameter in ABAQUS software [15]. Ice ball impact experiments were conducted by Kim et al. [16], Rhymer [17], and Tippmann et al. [18]. In the present work, the simulated hail ice (SHI) consists of 8-node reduced integration hexahedral elements (C3D8R element type in ABAQUS/Explicit), shown in Figure 3.

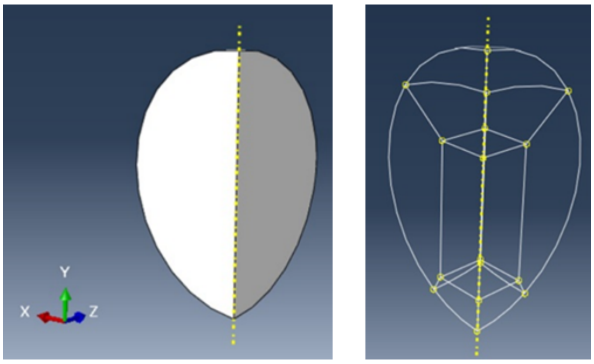


Figure 2. Quarter hemi-spherical sketch of hailstone

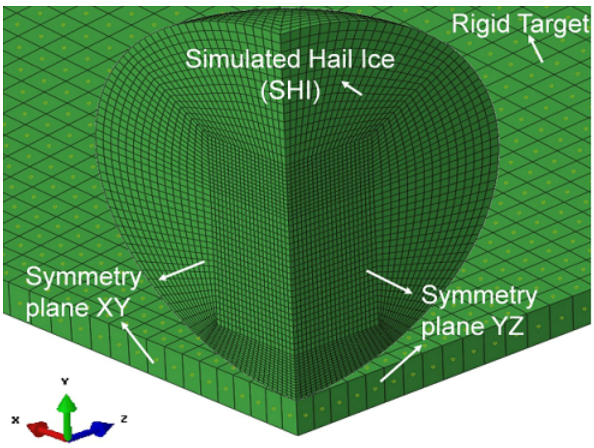


Figure 3. Quarter model biased mesh of 50.8mm diameter SHI and rigid target

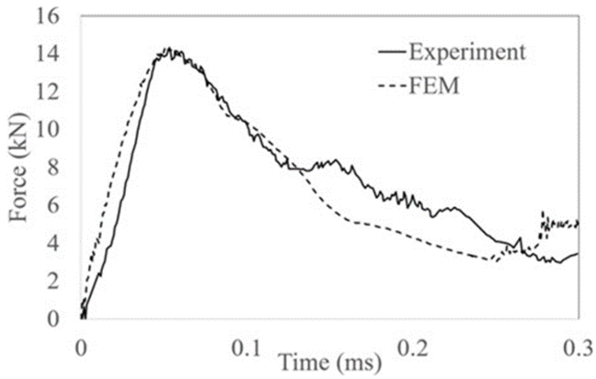
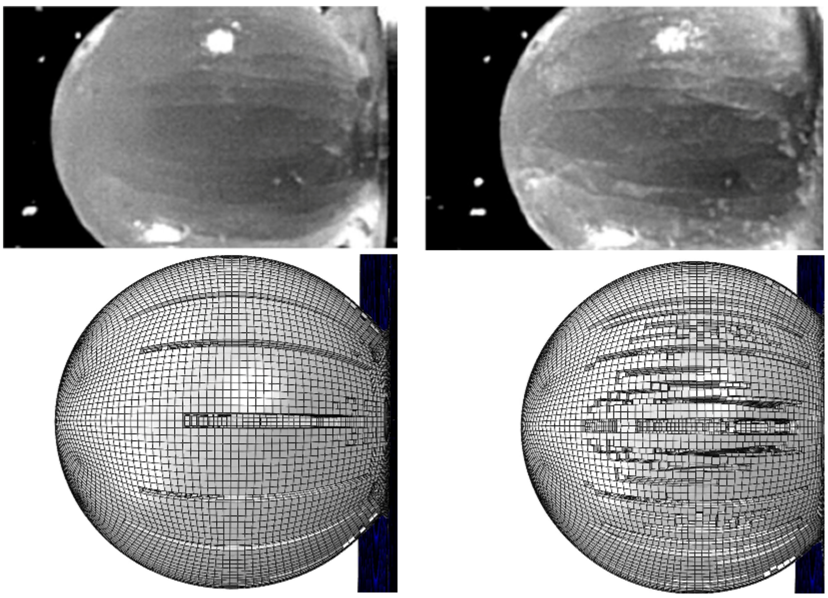


Figure 4. Force-Time graph FEM result with experimental test results UCSD 195 by Tipmann [14]

Figure 4 shows the force-time graph of the current finite element model and the experimental results of Tippmann [14]. The impact force histories of a 50.8mm ice ball specimen (UCSD 195) hitting the force measurement bar (the rigid target) at 60.6m/s are shown in Figure 4.

Tippmann [812] employed FEM with the same density. In this study, the density of each specimen was measured differently, and this value was applied. The authors used Tippmann's [14] specimen name UCSD 195 (with a 50.8mm diameter at 60.6m/s) and the same density for validation purposes. A deformable model was created for steel sheets. Steel has a density of 7.85 kg/m^3. Steel has an elastic modulus of 200GPa. The steel sheet's yield stress is 320MPa [19]. Timber batten is an additional component for the finite element model. Another crucial requirement for a successful finite element model is meshing. Hailstones are made with biased mesh, as given in Figure 3. The hailstone's impact zone split more sections than other edges to increase the study's sensitivity. The SHI projectile was modelled using a Lagrangian mesh. In Abaqus/Explicit, linear elements with decreased integration were employed to decrease time. There was hard, frictionless contact between the hailstone plate's outer surface. The bulk viscosity is 1.2 in the linear case and 0 in the quadratic case. One of FEM's limitations is vibration. An analysis of the vibration's spring-back effect was conducted. By drawing a path from one edge to the other, the depth of the dent was determined. The finite element analysis results match the laboratory test results quite well, as demonstrated in Figure 4, with the corresponding still images shown in Figure 5. For better clarity, the quarter model results are patterned cylindrically to represent the view of a complete SHI. The force-time history result of the present work is quite consistent with the laboratory test results in terms of the peak force magnitude and impulse. The finite element simulation matches the experimental cracking phenomenon with the failed elements propagating from the impact interface to the backside.



(a) 36μs (b) 135μs

Figure 5. Comparison between experimental observation and FEA simulation: 50.8mm SHI at 60.6m/s (114J)

3 Results and Discussion

After the hailstone situation impacted, the steel sheets were recorded with velocities. These two methods were based on making the hailstones have a higher rate of resisting breaking, but the method of liquid nitrogen showed better results than the PVA addition method. In the impact test, the material properties of liquid nitrogen were modelled using ABAQUS software [15]. Dent depth was measured using experimental and finite element methods. shows that just five of twenty-seven artificial hailstones were shattered. Four categories of projectile integrity were used in this study: major fragmentation, shattered, partially intact, and whole [12, 13, 20].

The experiment specimen from Wu [8] was modeled using ABAQUS [15]. Dent depths were measured in this study using two different techniques. Gauge and 3D scanner are these. The current study included the FEM results for Wu's [8] investigation. In this validation, three plate thicknesses (t), 1mm, 0.75mm, and 0.55mm, were included. Hailstones ranged in diameter from 26.3mm to 50.8mm. In Table 2, the denote of VR displays the hailstones' decreased velocity. Dh and Vc are the diameter of the hailstone and the velocity of the hailstone measured by a high-speed camera, respectively.

The FEM solution was displayed near the dent depths of the 3D scan. A millimeter is the difference between the FEM findings and the experimental dent depths, D. There is a 0.01mm discrepancy between the 3D scan dent depth and the FEM dent depth of specimen 50-4-2, indicating a good correlation between the two. The experimental and FEM results of the current study are displayed in Table 3. The hailstone's nominal diameter was 45mm. The average velocity was 28.78 m/s, and the average mass was 45.94 gr. The steel sheets had the following thicknesses: 0.30mm, 0.45mm, 0.60mm, 0.70mm, and 0.80mm.

Table 2. Dent depth comparison with Wu [8] and FEM results

Test Number	t (mm)	D_h(mm)	Mass (Gram)	V_c (m/s)	Dent Depth (mm)			Impact Energy (Joule)	VR (m/s)
					Gauge	3D scan	FEM		
50-15-2*	1.00	50.7	65.8	36.2	3.30	3.75	4.41	43.1	2.1
50-10-3*	1.00	50.0	64.6	29.2	2.20	2.48	3.12	27.5	2.1
50-15-1*	0.75	50.8	66.1	34.8	4.05	4.70	4.92	40.0	1.5
50-15-1	0.55	50.2	63.2	35.6	3.90	4.84	4.69	40.0	1.9
50-15-2*	0.55	50.2	64.0	36.5	3.90	4.85	5.08	42.6	2.0
50-4-1	0.55	47.9	59.7	18.4	1.40	1.76	1.11	10.1	1.0
50-4-2	0.55	49.0	62.0	22.4	1.60	2.07	2.08	15.6	1.8
45-14-2	0.55	45.2	47.8	34.3	3.75	4.08	4.83	28.1	1.3
45-5-1	0.55	44.9	46.3	19.6	1.50	1.79	1.17	8.9	0.8
45-4-3	0.55	44.8	46.0	22.2	2.55	2.98	2.85	11.3	2.1
38-12.5-2	0.55	38.1	27.8	33.5	3.30	3.28	2.39	15.6	1.5
38-4-2	0.55	38.0	26.9	19.3	1.25	1.72	1.04	5.0	0.5
38-4-1	0.55	37.8	27.1	18.6	1.25	1.67	0.98	4.7	1.7
33-11-1	0.55	33.3	19.1	37.1	2.70	3.10	2.54	13.1	0.8
33-6-3	0.55	32.5	18.3	26.1	1.90	1.88	1.61	6.2	1.5
25-6-1*	0.55	25.5	9.2	32.8	1.35	1.74	1.41	4.9	2.4
25-6-3	0.55	26.3	9.9	32.1	1.40	1.68	1.44	5.1	0.9
25-3-4	0.55	26.3	10.2	16.1	0.50	0.72	0.68	1.3	0.4

Table 3. Test results of 45mm diameter hailstone

Test ID	t (mm)	D_h (mm)	Mass (Gram)	V_c (m/s)	D (mm)(Gauge)	D (mm)(FEM)
G300/0.60/45/3	0.60	43.46	46.50	33.40	3.18	2.85
G300/0.70/45/8	0.70	44.22	45.80	23.12	1.67	2.02
G300/0.70/45/7	0.70	44.71	48.90	30.06	2.78	2.70
G300/0.80/45/1	0.80	43.72	44.50	28.69	2.34	2.15
G300/0.80/45/9	0.80	44.68	45.90	27.55	2.31	2.10
G300/0.45/45/2	0.45	44.53	45.00	30.06	2.95	2.94
G300/0.45/45/4	0.45	45.17	46.40	28.69	2.94	2.91
G300/0.30/45/9	0.30	44.86	44.50	28.69	3.87	4.15

The G300/0.45/45/2 and G300/0.70/45/7 dent depths are given in Figure 6. Hailstones were composed of 88% demineralized water and 12% PVA. The hailstones have a diameter of 44.71mm and 44.53mm for the specimens G300/0.45/45/2 and G300/0.70/45/7, respectively. These two hailstones are traveling at 30.06 m/s. The thickness of the target steel sheets is 0.70mm and 0.45mm. Dent depth was found using FEM in close agreement with test findings. Dent depths of the specimens ranged from 2.78mm to 2.95mm, depending on the thickness of the steel sheet.

It was determined from the test results that the impact test had been completed and that hailstone had successfully simulated the impact. Thus, permanent deformation (such as that of the specimens used in this study) can be predicted with high accuracy for a given set of impact conditions and the material properties of the non-rigid impactor object.

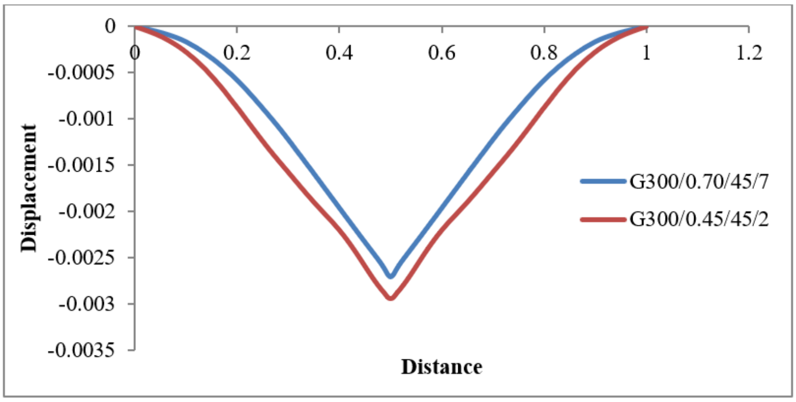


Figure 6. Dent depth for two 45mm diameter hailstones

4 Limitations

The current study has limitations. Measurement of hailstone velocity and dent depth are the main limitations. The velocity of the hailstone can be measured from the impacted moment. Dent depth was also measured using a depth caliper. It can depend on the person who is measuring. Another limitation is that the thickness of the steel sheet is nonuniform. Against all these limitations, hailstones were impacted with terminal velocity. FEM was created, and experimental results and finite element results were close.

5 Conclusions

The current paper presented the experimental facility for hailstone impact tests, including the equipment for launching ice balls, which is located in the High Bay Lab of the Department of Civil Engineering Main Campus, Adnan Menderes University (ADU). Ice balls of various masses are fired onto steel roofing and cladding materials at different velocities to provide experimental data on the effects of hailstone impact on steel sheets having different hailstone diameters, terminal velocities, yield stresses, and thicknesses. According to the study, the impact energy, sheet metal thickness, and hailstone diameter are the major factors affecting the depth of the dents. Although hailstones vary in size, they can all undergo similar long-term deformations as a result of variations in momentum. A smaller hailstone with a higher momentum may produce a comparable long-term deformation as a larger hailstone with a lower momentum when both have an identical impact energy. Comparing the outcomes of experimental measurements to precise predictions of the deformation in the FE models has not proven to be successful. FE models typically overestimate steel panel elastic response. Furthermore, since the hardness of the hailstone affects the impact force generated at the point of contact, an independent effort is required to determine the strain sensitivity of artificial hailstone precisely. These discoveries will make the development of new design techniques for steel sheeting's ability to withstand hail possible. These techniques will be more widely applicable, comprehensive, and in tune with the environment.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] L. M. Leslie, M. Leplastrier, and B. W. Buckley, "Estimating future trends in severe hailstorms over the Sydney Basin: A climate modelling study," *Atmos. Res.*, vol. 87, no. 1, pp. 37–51, 2008. https://doi.org/10.1016/j.atmosres.2007.06.006

[2] B. A. Niemeier and C. E. Burley, “Hailstone response of body panels-real and simulated,” *SAE Technical Paper 780398*, 1978. https://doi.org/10.4271/780398

[3] S. Nomura, Y. Yutori, J. Iwaya, M. Miyahara, and I. Kokubo, “A study of the dynamic dent resistance,” in *Efficiency in Sheet Metal Forming, IDDRG 13th Biennial Congress*, 1984, pp. 394–402.

[4] P. T. Vreede, “The influence of material properties and geometry on dynamic dent resistance: Experiments and simulations,” in *Proceedings of the International Body Engineering Conference, (IBEC), Detroit, Michigan, USA*, 1995.

[5] M. F. Shi, J. A. Brindza, P. F. Michel, P. Bucklin, P. J. Belanger, and J. M. Prencipe, “Static and dynamic dent resistance performance of automotive steel body panels,” *SAE Technical Paper 970158*, 1997. https://doi.org/10.4271/970158

[6] J. M. Swift, “Simulated hail ice mechanical properties and failure mechanism at quasi-static strain rates,” Ph.D. dissertation, University of Washington, 2013.

[7] M. E. Uz, G. Yilmaz, and T. Bircan, “The making of a hailstone simulated realistic damage,” *J. Eng. Sci. Des.*, vol. 5, no. 2, pp. 411–423, 2017. https://doi.org/10.21923/jesd.327312

[8] Y. F. Wu, “Determining the effects of hailstone impact on flat cold-reduced steel roof sheeting,” Master’s thesis, University of Wollongong, 2018. https://ro.uow.edu.au/theses1/192

[9] G. Yilmaz, M. E. Uz, M. Dawood, and D. Kop, “Production of artificial hailstone with liquid nitrogen and comparisons with other artificial hailstones up to now,” *J. Eng. Sci. Des.*, vol. 8, no. 4, pp. 1180–1189, 2020. https://doi.org/10.21923/jesd.672264

[10] J. A. P. Laurie, *Hail and Its Effects on Buildings*. Council for Scientific and Industrial Research, 1960. https://books.google.com.tr/books?id=sA3TGwAACAAJ

[11] T. Bircan, M. Uz, H. Kirnak, E. Erdem, M. Goren, and D. Kop, “Investigation of a theory for determining hailstone resistance,” in *Proceedings of the 13th International Congress on Advances in Civil Engineering, Izmir, Turkey*, 2018.

[12] M. E. Uz, M. D. Kop, and E. M. Yildirim, “Analysis of out-of-plane hail impact resistance of steel roof panels,” *Exp. Tech.*, vol. 46, no. 3, pp. 509–527, 2022. https://doi.org/10.1007/s40799-022-00550-z

[13] M. E. Uz, M. D. Kop, and E. M. Yildirim, “Determining the empirical model for estimating the permanent deformation in flat roof panels under hail impact,” *AIP Adv.*, vol. 11, no. 12, p. 125117, 2021. https://doi.org/10.1063/5.0069617

[14] J. D. Tippmann, “Development of a strain rate sensitive ice material model for hail ice impact simulation,” Ph.D. dissertation, University of California, San Diego, United States, 2011.

[15] ABAQUS, *Version 6.14 User’s Manual*, Dassault Systèmes Simulia Corp.; Providence, RI, USA, 2014.

[16] H. Kim, D. A. Welch, and K. T. Kedward, “Experimental investigation of high velocity ice impacts on woven carbon/epoxy composite panels,” *Compos. Part A Appl. Sci. Manuf.*, vol. 34, no. 1, pp. 25–41, 2003. https://doi.org/10.1016/S1359-835X(02)00258-0

[17] J. D. Rhymer, “Force criterion prediction of damage for carbon/epoxy composite panels impacted by high velocity ice,” Ph.D. dissertation, University of California, San Diego, United States, 2012.

[18] J. D. Tippmann, H. Kim, and J. D. Rhymer, “Experimentally validated strain rate dependent material model for spherical ice impact simulation,” *Int. J. Impact Eng.*, vol. 57, pp. 43–54, 2013. https://doi.org/10.1016/j.ijimpeng.2013.01.013

[19] M. D. Kop, “The effects of hail impact on steel roofing profiles with FEM and laboratory tests,” Master’s thesis, Aydın Adnan Menderes University, Fen Bilimleri Enstitüsü, Turkey, 2022. http://hdl.handle.net/11607/4934

[20] M. E. Uz, “Modelling the impact of hailstones on flat steel roofing membranes for residential buildings,” *Sci. Rep.*, vol. 12, no. 1, p. 19836, 2022. https://doi.org/10.1038/s41598-022-24375-3