INTERNATIONAL JOURNAL of ENGINEERING SCIENCE AND APPLICATION
Q. Xie, Vol.7, No.1, March 2023

Numerical Study of the Hail Impact on PV Panel by Specific Constitutive Models

Qi Xie *

* Clenergy (Xiamen) Technology Co., Ltd. Xiang'an District, Xiamen, Fujian 361101 P.R.China

‡ Corresponding Author; Tel: +60 1125583897

Corresponding email: qiconsultor@163.com

Received: 05.09.2022 Accepted:27.03.2023

Abstract- In this article, author mainly addressed on the impact problem between hail and glass in photovoltaic(PV) panel, and solved several issues by finite element analysis, firstly, based on historical experiments and simulations, author demonstrated the applied criteria about numerical hails and glass constitutive models, identified that "EPF" and "Epoxy with stochastic variances(SV)" constitutive models can be the candidates of the research objects respectively, then author applied the 'SHP' (Smooth Particles Hydrodynamics) method on 'LS-Dyna' and performed several impact simulations to assess their mechanic behaviours, meanwhile, compared simulation values with previous experiments [1], these study indexes include kinetic energy, shear stress and deformation, etc. Finally, author established the dependencies charts of glass deformations with stochastic variances and hail falling speeds, proposed series conclusions about the glass damage prediction from SV parameters, these conclusions can be references for failure predictions of PV panels. The novelty of this article is that author imported the stochastic variances parameters in glass model, expressed the guidelines and the conditions for adopting the hail and glass mathematical models for numerical study. This article can benefit the research in destructive failure and material failure morphonology, especially in solar power industry, car industry, etc.

Keywords Glass, Hail, LS-Dyna, Smooth Particles Hydrodynamics (SPH), Stochastic Variance.

1. Introduction

The scenarios that impact among hailstones and glass are very common phenomenon in nature and human society, the probability of severe climate (Hailstones) shows obvious increasing in the foreseeable future [1, 3]. Hailstones which are considered as the derivative compositions from ice and other natural solid mixtures (the ice material forms the outline of hailstones), are widely found in most parts of the Earth, their impact energy could be magnificent, usually proportional to their mass and falling speed. Especially, their impact on industry products and equipment in the openair usually caused unpredictable and uncountable loss, such as the crack damage on safe glass which equipped on cars, the destructive collisions on the photovoltaics (PV) panels in solar power stations. (Figure.1(a), (b))

The problem that how to simulate the mechanic behaviours between hail and glass jumped out the paper and missioned researcher to explore their characteristics. As development of Finite Element Analysis (FEA), it is possible to simulate mechanical behaviours easily, researchers can predict the subsequent behaviours from the simulation and water down the loss for human society.

Fig. 1(a). The multiple impacts on in serving aircraft [1]

Fig. 1(b). Hailstorm collapsed and affected PV Module [2]

In this article, the findings of the proper constitutive models of Hailstone and Glass are the priority issues, from perspective of hail material, surveys such as that conducted by previous researchers have shown that, in static state or quasi-static, hailstone can be simulated by 'Mohr-Coulomb' Model and 'User-define(Exponent) model' [4, 5][, however, because of the special mechanic properties of ice material, their failure criteria and morphology will experience 'ductile' to 'brittle' transition under the compression with high strain ratio[6, 7]. when hailstones run in high speed, the models with kinetic property can be the best option, these models including 'Elastic-Plastic Failure' model (EPF), 'Elastic-Plastic Hydro' model (EPH) [8, 9], etc. Regarding 'Glass' model, Glass materials can be made of various chemical compositions and fabricated by different processes, which affect their mechanical, electrical, chemical, optical, and thermal properties[10], most researchers are inclined to use common glass model(soda lime) to perform simulation, despite that, there are preferable models for deeper study in LS-Dyna material library, such as piecewise linear plastic model(*Mat_280), piecewise linear plastic with stochastic model(*Mat_24), composite-damage model (*Mat_22)[11], and epoxy model. After chewing the relevant academic paper, most of these glass models only experienced rigid body impact without any stochastic factors, and no records of contact with hailstones been found yet, thus it is valuable to deploy some improvement on both constitutive models.

2. Constitutive Models and Methodology

During the simulation procedure, in terms of hail models, the EPH model needs equation of state (EOS) during the process of ice collapse, however, these parameters are not available all over time, to enhance the generic approach in civil and industry applications, author locked the 'Elastic-Plastic Failure' model (EPF) as the hail constitutive model. As for the glass models, despite that several constitutive models mentioned above, which can be applied in the impact scenario as well, according to the renewable industry trends and demands, for glass samples, author focus on the Glass (Epoxy +SV) type. The impact algorithm and simulation process followed the 'Smooth Particles Hydrodynamics' (SPH) theory. Their mechanic constitutive properties will be demonstrated below:

2.1. Elastic-Plastic Failure Model (Hail by Epf Model)

Hail projectiles are typical condensed ice solid, the mechanic properties shown elastic and plastic characteristics when the impact speed changed, which can be identified by intensity of strain ratio as well. For high-speed impact scenario, to strengthen the model compatibility, the "plasticity with simple plastic strain failure" could be the mandatory property for hail projectile models. Reviewing similar material in ANSYS library, it is expected to apply *Mat_13 Elastic-Plastic-Failure (EPF) to simulate the hail projectiles, the parametric details can refer Table.1.

2.2. Glass with Stochastic Failure Control (epoxy+sv)

In most recent studies, the glass material has been simulated by several constitutive models which mentioned above, however, no stochastics variance (SV) applications have been found in Glass (Epoxy) model by far, as their fractures followed the random factors control, hence, it is worth to deploy the glass impact with failure stochastic variances during the impact process. From the statistic methodology, the probability of nature disaster occurrence follows the "gamma" distribution, to be more precisely, Mott distribution[12], which is one of the gamma distributions, can describe most stochastic phenomenon, and could be expressed in Eq. (1) as well:

$$P(\varepsilon) = 1 - \exp\left[-\frac{C}{\gamma}(\exp(\gamma\varepsilon))\right] \quad (1)$$

Where: P is the probability of fracture, ε is the strain, C and γ are the material constants.

2.3. SPH Method

Smooth Particles Hydrodynamics (SPH), which is wildly used and known for its ability to simulate a natural flow of material without mesh distortion problems based on the Finite Element Method (FEM), is the most suitable method to simulate the hail impact and its discretion forms. The earliest application can be found earlier 1990' years[13] in solid mechanic and aerospace debris collapse simulations, as the development of computer science, this standard method was updated and improved by new algorithms and the consequent derivative versions are still affect the present works, such as adaptive SPH[14], MLSPH[15], Gamma SPH[16], δ-SPH[17], Corrective SPH (CSPH)[18]et al., no matter what kind of practical scenarios applied, most of them follow the same basic theory which list below:

In SPH method, the quantities of particle i can be approximated by the direct summation of the relevant quantities of its closed particles j.

The continuity Eq. (2) can be approximated as follows:

$$\frac{D\rho i}{Dt} = m_i \sum_{j=1}^{N} \frac{m_j}{\rho_j}(v_i^\alpha - v_j^\alpha)\frac{\partial W_{ij}}{\partial x_i^\alpha} \quad (2)$$

Where ρ_j and m_i are the density and mass of particle i with velocity component v_i and m_j are the density and mass of particles j which has velocity component v_j. Obvious that SPH formulars expressed by partial differential equations governing the particles states.

From the initial state (before impact, state 1), the kinetic values from hail projectiles can be expressed in Eq. (3) and Eq. (4) below:

$$E_1 = T_1 = \frac{1}{2}mv_0^2 \quad (3)$$

Consequence state (when impact on glass, state 2):

$$E_2 = T_2 + V_2 = \frac{1}{2}mv^2 + V_{shear} + V_{other} \quad (4)$$

From the law of energy conservation demonstration, another energy form can be expressed in Eq. (5):

$$E_2 - E_1 = W_{nc} \quad (5)$$

Where W_{nc} is the non-conservative work which occurs during the state 1 to state 2, which can be considered as the energy dissipating which cannot measurement accurately but read by bundled energy package. As per Kim and Kedward s' observation results [10], when impact kinetic energy beyond the threshold values, the surface glass will be pierced, the relevant simulation values will be list in the consequent Figurers.

From the demonstration above, the full set of parametric values of each constitutive model and Photovoltaic panel can be written in Table.1(a) (b), below:

Table 1(a). Parametric of each constitutive model

Hail (EPF)	Value	Unit	Glass (Epoxy)	Value	Unit
Density	846	Kg/m^3	Density	1506	Kg/m3
Elastic Shear Modulus	3.46	Gpa	Young's Modulus X	71.7	Gpa
Yield strength	10.3	Mpa	Young's Modulus Y	69.5	Mpa
Hardening Modulus	6.89	Gpa	Young's Modulus Z	68.9	Gpa
Bulk Modulus	8.99	Gpa	Poisson Ratio XY	0.038	
Plastic Failure Strain	0.35	%	Poisson Ratio YZ	0.03	
Tensile failure pressure	-4	Mpa	Poisson Ratio XZ	0.029	

Table 1(b). Parametric of Photovoltaic panel

Items	Density	Unit	Young's Modulus	Unit	Poisson Ratio
Encapsulant	1030	(Kg/m^3)	0.067	GPa	0.33
Silicon (solar cell)	2330	(Kg/m^3)	130	GPa	0.24
Back Sheet	1100	(Kg/m^3)	2.3	GPa	0.41

3. Numerical Simulations and Results Analysis

The impact scenarios can be described following: the hail projectile falling on the glass panel (Impact Core area with radius R=0.3m) with different impact speeds and stochastic variance [0.1~0.9], for instance, in the 1st group, given SV=0.1 functioned on glass model, deploying the numerical simulation of the hail projectile impact on glass with speed from 40m/s to 100m/s. For the 2nd group test, given SV=0.2 ,functioned on glass model, the hail impact on panel following the same operations as the first group, other groups followed the same procedure as 1st and 2nd group, till SV=0.9. Nine simulation results data sets can be acquired from whole process repeatedly, these simulation results data consist, kinetic energy, equivalent stresses, and deformations, etc.

3.1 Numerical Simulations:

Following the renewable industry standard, the glass dimension equipped on PV panels, usually adopted the dimension of 2000mm×1000mm× (3.5~4.2) mm with length, breadth, and thickness respectively. The panel formed by several layers materials which protect the inner electricity generate units (crystalline silicon), such as encapsulant and back sheet, etc. Hail projectiles dimensions can refer previous statistic data, the max diameters are no more than 50mm, the generic panel sectional view can be depicted in Figure.2 below:

3.2. Results Integrating and Analysis

3.2.1 Kinetic Energy Analysis

To verify the simulation results, it is compulsory to compare relevant results between simulation and theoretical calculation, it is easy to calculate the kinetic energy of hail projectile impact on panel at the very contact moment, refer Eq. (3), based on simulation results, we can establish the

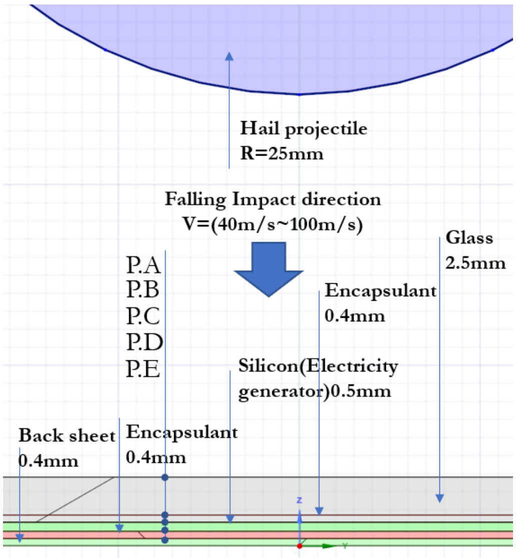

Fig. 2. Scenario of hail impact on PV panel core area & Structure depiction of PV Panel

chart above in Figure.3:

From Figure.3, on the one hand, it is obvious that there are negligible disparities between simulation values and theoretical values, on the other hand, the max kinetic energy from hail projectile is 291(J), from Kim and Kedward's experiments results (Table.4) [10], the exert kinetic energy for breaking panel should larger than 95(J), V=73m/s. The vertical blue dash line defined the glass failure border, if over these values, the hail projectile could break through the glass at the very contact moment, the Figure.6(a)~Figure.6(c) also reflect this view. Furthermore,

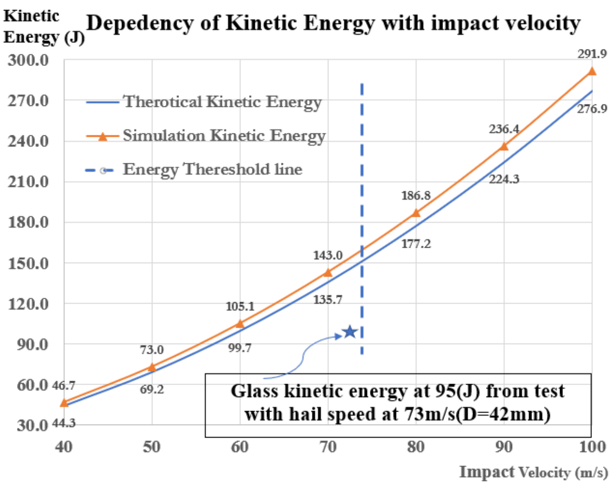

Fig. 3. Hail impact kinetic energy

the numerical models are stable and robust at the initial impact moment.

Collecting the simulation results, it is easily to capture the failure morphology of glass splashed toward different directions with random fragments, these were affected by different stochastic variances (SV=0.1,0.5,0.9) as well, the

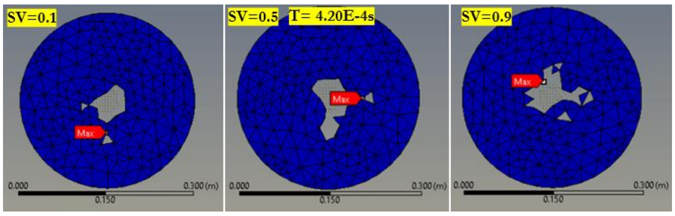

Fig. 4(a). glass performances after impact when t=4.2E-4s

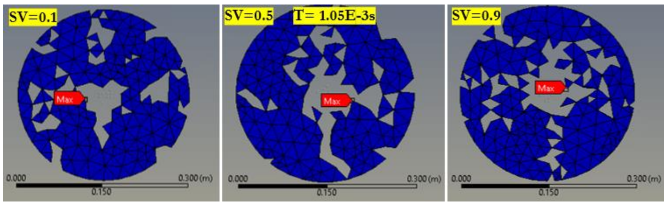

Fig. 4(b). glass performances after impact when t=1.05E-3s

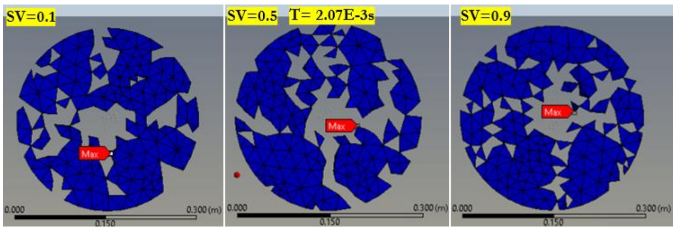

Fig. 4(c). glass performances after impact when t=2.07E-3s

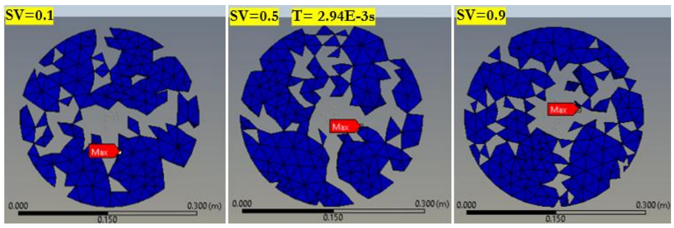

Fig. 4(d). glass performances after impact when t =2.94E-3s

glass core area impact simulation details can refer the Figure.4(a)~4(e).

Form the Figure.4(a)~4(d), when impact speed at V=100m/s, it is easily to find the panel surface glass already crashed by hail projectile, due to the stochastic variances participations, glass crack trends and directions showing irregular, extracting initial breakthrough time t =0.42ms to the last cracking checkpoint at t=2.94ms, when SV=0.1, the break area diffused from hail contact centre to adjacent area around, when SV=0.5, the break area and fragments appeared more discretely than SV=0.1, especially, more breakthrough lines showing in the impact centre and core area edge, when SV=0.9, the degree of discretization of break area perform the same trend like SV=0.5, but larger area around impact centre, the core edge showed more fragments and crack lines than others. It is notable that the fragments dimensions of failure criteria are also controlled by mesh methods which are based on explicit solutions. From Figure4(e), the hail projectile cracked and splashed

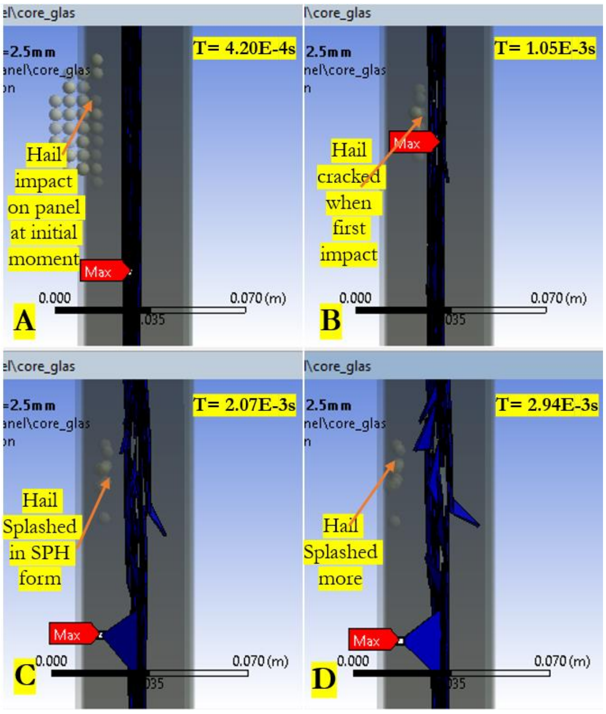

Fig. 4(e). Hail impact and failure forms

from integrate solid into collapse particles, which are shown from "A" to "D", the cracking forms and splashing trends performed irregular from the impact centre to adjacent area. In terms of glass blast, the failure forms reflected the actual cracking styles and splashing directions, fit the scenarios (Figure.1(b)).

In this article, author mainly focus on hail and glass impact, other material embedded in the PV panel will be described slightly from the simulation results, as under the condition that when the impact speed reached 100m/s, it is firmly that the PV panels are already destructed by the large deformations transferred from surface to the core parts (Silicon electricity generator), the crystalline silicon electronic analysis will be discussed in another paper, Therefore, marking the check points "P.A", "P.B", "P.C", "P.D", "P.E" on each layer surface from the top to the bottom(Figure.2), and it is possible to illustrate the dependency of each layer deformations with impact timeline

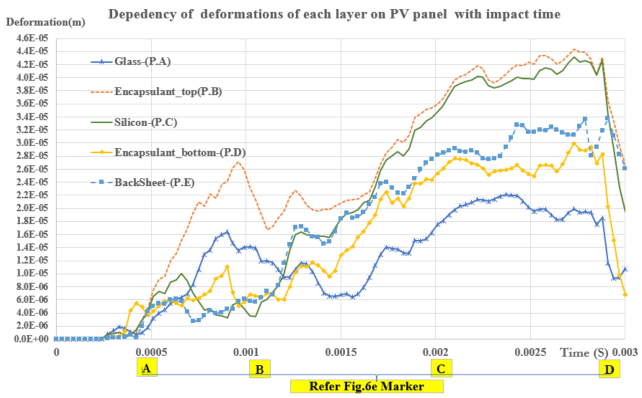

Fig. 5(a). Deformation of each layer on PV panel

in Figure.5(a) below.

From Figure.5(a), it is obvious that after the hail impact on the glass layer, the low stiffness encapsulant (orange line-P.B and P.D) with high Poisson ratio, which beneath the glass and silicon layer respectively, absorbed most energy, the deformations start at "A" point, performed larger than other layers at "B" point, silicon layer (green line) as the sequent solid layer behaved smaller deformation than encapsulant after "A" point, as the impact energy was dissipated by the upper encapsulant, however, due to its stronger stiffness, the react of larger deflection rebounded swiftly after "B" point, which means hail projectile completed the full impact, and continued climbing up to the maximum value near "D" point, which is the last observation moment as well. In the meantime, compared with other lines in the same period, glass displacement (blueline-P.A) performed a bit weaker than silicon, it is highly possible that glass was already in failure and discreet state as the energy dissipated after the full impact and the mesh node could be vanished after their failures. The back sheet (Blue dash line) as the last fence of panel, reacted in moderate deformation at the last phase till all energy dissipated.

3.2.3 Model Quantity Analysis

Hourglass energy and internal energy are also the critical parameters to evaluate the models' quantities, from the principle of explicit solution algorithm, for non-tetrahedron mesh mode, the max ratio of hourglass and internal energy should no more 10%, or model will show over stiff behaviour than the real performance[19], for tetrahedron meshed model, including the 2nd order tetrahedron, the hourglass energy should equal to zero, hereby, extracting the related results and establish the charts in Figure5(b).

From Figure.5(b), hourglass energy always keeps in zero when the core area glass adopts tetrahedron mesh method (Refer Figure.4 series) and the results fit the explicit algorithm regulations and assumptions.

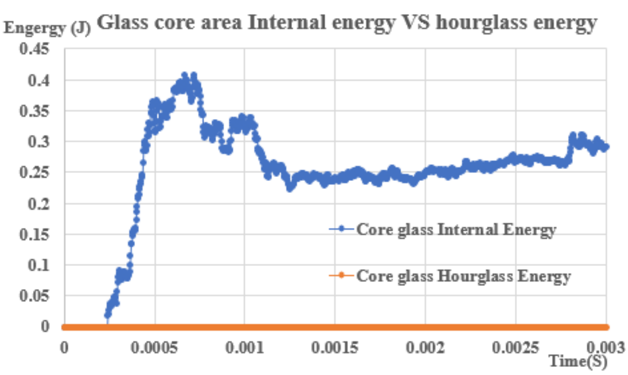

Fig. 5(b). Internal energy vs Hourglass energy

Overall, most of the deformations from each layer performed similar behaviours like the real scenario, the constitutive models can meet the requirements of numerical simulations.

3.2.4 Other Mechanic Indexes Analysis

To illustrate the PV panel surface mechanic behaviours from multiple dimensions, it is necessary to extract other mechanic indexes including the equivalent stress, glass core area deformations, and glass total deformations. Intergrading the simulation results from stochastic variances parameters (SV=0.1~0.9) participation, it is easily to draw the series charts below:

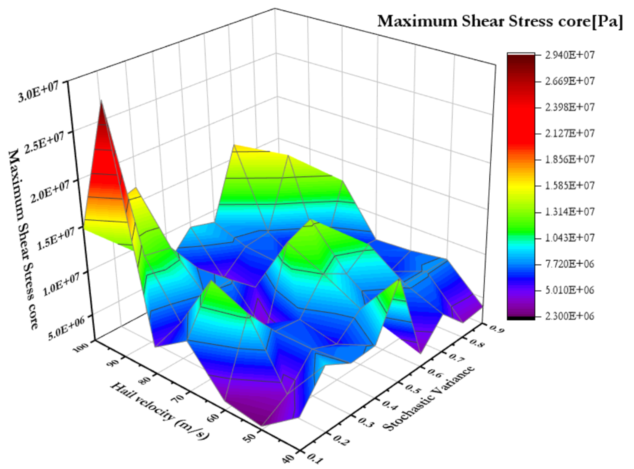

Fig.6(a). Distributions of Max shear stress in core area

From Figure.6(a), the maximum shear stress (29.4Mpa) located in contact core area, appeared at the impact speed around 70~90 m/s with the stochastic parameter SV=0.1 correspondingly. it is noticeable that impact with max speed may not obtain the max shear stress, as this value have high dependency with average shear stress and interlaminar shear modulus of composite panel [10].

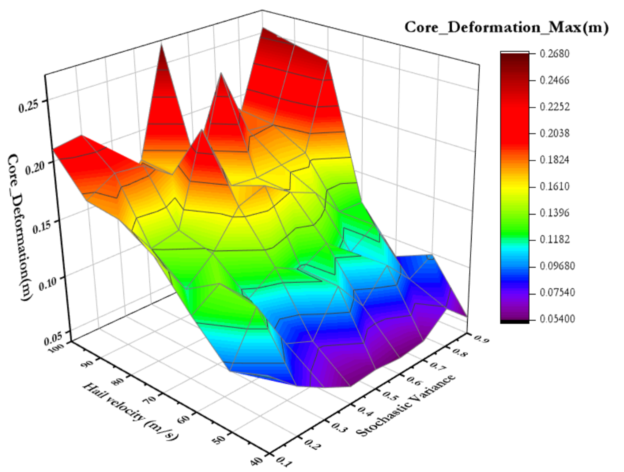

Fig.6(b). Max deformations in core area

From Figureure.6(b)above, the deformations fluctuated fiercely when impact speed over 70m/s, the max deformations (0.267m) appeared at the impact speed equal to 100m/s with the stochastic parameter SV=0.5, the max impact speed from hail projectiles, brought tremendous energy which can be measured from kinetic energy, broke through the glass into pieces randomly, and led the splash scenes, especially when SV=0.5, the displacement from splash reached the max. This simulation scenario can play a reference role for practical predictions.

Unlike the core area deformations, from the illustration of Figure.6(c)below, the whole glass deformations appeared more regular than the core area, no matter what kind of SV values involved, the whole panel displacement increased slightly before the impact speed over 70m/s, most of them located in the range of (0~ 0.001)m , before this impact speed, it is obvious that glass panel in the intact state all the time, which also can be considered as in the quasi-static state. When speed over 70m/s, the kinetic energy started to break the balance, pushed glass into fierce reactions until the glass been destructed with slices and fragments splashing, the corresponding energy threshold value fit the simulation and theorical results where can refer in Figureure.3.

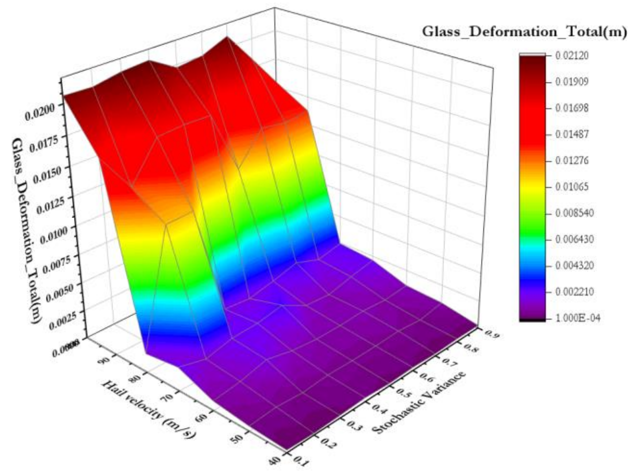

Fig.6(c). Deformations of whole glass panel

4. Conclusion

The main goal of the current study is to investigate the numerical simulations of hail impact on PV panel with the help of finite element analysis. Unlike previous paper, author chose the constitutive models with improved constitutive models (EPF) and (Epoxy + SV) on hails and glass, they are more approached to the industry applications with real working scenarios, albeit no discussions on the electronic performances from electricity generate units (crystalline silicon). From the simulation results, it is easily to make series conclusions as below:

(1) Both “EPF” Model and “Epoxy glass” model have ability to simulate the Hail and glass material mechanic well, under the condition of impact, the failure morphonology and trends

fit the previous observations, they can be considered as improved models for further research.

(2) The "SPH" method can afford the solution role for hailstones mesh and impact properly, the depicts of hail projectiles failure and splashed morphonology fit the actual impact scenario.

(3) When impact speed velocity located in the range of [70m/s, 100m/s], the deformations of glass impact core area with stochastic variances (SV) participation, showed irregular performances, especially when SV valued from 0.2~0.5, the larger distortions from deformations and equivalent stresses conducted the consequent glass behaviours.

(4) The stochastic variances (SV) have no strong dependency on the whole glass deformations, any SV candidate values could result similar deformations and trends.

(5) Due to the mesh methods on impact object which followed the explicit algorithm, fractional simulation results from meshed nodes cannot be read clearly or performed unreasonable distortion, but the main trends followed the real scenario, thus, the more precise results wanted, the higher mesh quantity should be deployed.

(6) The simulation results from Figure.6 series can provide a few samples for the glass impact failure prediction.

Acknowledgement

Thanks for the working experiences in Clenergy (Xiamen) Technology Co., Ltd, the numerical model parameters come from work survey and related academic paper. Far Eastern Federal University provided partial technical support.

References

[1] Field.P.R, H.W., Cappelluti G., McMillan A.,Foreman A., Stubbs D. and Willows M., Hail Threat Standardisation - EASA, in Final Report EASA_REP_RESEA. 2009

[2] Gupta, V., et al., Comprehensive review on effect of dust on solar photovoltaic system and mitigation techniques. Solar Energy.Vol. 191: pp. 596-622, 2019.

[3] Li, M., et al., A Statistical Analysis of Hail Events and Their Environmental Conditions in China during 2008-2015. Journal of Applied Meteorology and Climatology.Vol. 57, 2018.

[4] Xie, Q., Numerical modeling of the stress-strain state of the ice beam by specified constitutive model. Material Science, Engineering and Applications.Vol. 2(1): pp. 1–8, 2022.

[5] S471-04-General requirements, design criteria, the environment, and loads, Canadian Standards Association. Mississauga, Ont. 2004

[6] Schulson, E.M., The structure and mechanical behavior of ice. JOM Journal of the Minerals Metals and Materials Society.Vol. 51(2): pp. 21-27, 1999.

[7] Jones, S.J., A review of the strength of iceberg and other freshwater ice and the effect of temperature. Cold Regions Science and Technology.Vol. 47(3): pp. 256-262, 2007.

[8] Anghileri, M., et al., A survey of numerical models for hail impact analysis using explicit finite element codes. International Journal of Impact Engineering.Vol. 31: pp. 929-944, 2005.

[9] Kimand, H. and K. Kedward, Experimental measurement and Numerical prediction Hail Ice Impacts and Predicting Impact Damage Initiation in Composite Structures. Aiaa Journal - AIAA J.Vol. 38: pp. 1278-1288, 2000.

[10] Daryadel, S.S., et al., Dynamic response of glass under low-velocity impact and high strain-rate SHPB compression loading. Journal of Non-Crystalline Solids.Vol. 432: pp. 432-439, 2016.

[11] Yong, M., L. Iannucci, and B.G. Falzon, Efficient modelling and optimisation of hybrid multilayered plates subject to ballistic impact. International Journal of Impact Engineering.Vol. 37(6): pp. 605-624, 2010.

[12] Mazonka, O., Cumulative Probability of Blast Fragmentation Effect. arXiv: General Physics, 2013.

[13] Libersky, L. and A. Petschek, Smooth particle hydrodynamics with strength of materials', in Advances in the Free-Lagrange Method. pp. 248-257. 2006

[14] Hu, D., et al., Analysis of explosion in concrete by axisymmetric FE-SPH adaptive coupling method. Hu, Dean.Vol. 31, 2014.

[15] Gary A. Dilts, Moving least-squares particle hydrodynamics ii: conservation and boundaries, Int. J. Numer. Methods Eng.Vol. 48(10): pp. 1503-1524, 2000.

[16] Limido, J., et al., Modeling of Hypervelocity Impact Experiments Using Gamma-SPH Technique. V004T004A021. 2017

[17] Molteni, D. and A. Colagrossi, A simple procedure to improve the pressure evaluation in hydrodynamic context using the SPH. Computer Physics Communications.Vol. 180(6): pp. 861-872, 2009.

[18] Chen, J.K., J.E. Beraun, and C.J. Jih, An improvement for tensile instability in smoothed particle hydrodynamics. Computational Mechanics.Vol. 23: pp. 279-287, 1999.

[19] ANSYS, Workbench LS-DYNA (ACT Extension) Training, in Element formulations. 2016