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Dynamic Analysis and Validation of Crack Propagation in Laminated Glass Using Peridynamics

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Abstract: *Use of glass is increased in almost every part of life. Glass undergoes from the various stages when it gets ready, and analysis of glass is one of the important stages. So in this project focus is concentrated on the analysis of glass by conventional FEA method and modern Peridynamic method.*

Glass is modelled in the Solid-edge Modeling software, then model is imported in the Hypermesh software and meshing is done. Later analysis is done by importing the meshed model in the LS DYNA software. First single layered glass is analyzed by applying the local FEA method (MAT_32 material model), as a result glass shown the deformation of 10mm which is not true. This happened because local FEA method uses differential equations (DE) to solve the model. And DE can be used only when there is continuity in the material. So later new card was introduced in the LS DYNA which replaced DE by Integro-Differential Equations which can be used for the discontinuous material also which has cracks. SECTION_SOLID_PERI control card is used and by this Peridynamics method the deformation observed was 3.8mm.

Later the analysis is extended to laminated glass (LG). The drop test was performed on the glass and results are taken. And with the same boundary conditions as that of experiments the analysis is carried, and the results are compared with experiment results. The kinetic energy, fractured area and the crack propagation matched to experiment one and hence non-local FEA method Peridynamics proves to be the best technique to analyse brittle fracture.

Keywords: Peridynamics, MAT_32, Laminated Glass, Crack Propagation, Horizon

I. INTRODUCTION

We are living in 21st century, where growth of science and technology has taken place at a such high level thatwrong use of technology is being done. And as a result of it, public strikes, wars, terrorism and violence are increasing day by day. The terrorist attack on Taj hotel Mumbai and Parris attack are the recent examples of it. Inthis scenariosafety of individual become the matter of concern. And bullet resistant glass (safety glass) is the primary protective option for such fatal attacks. While such kind of safety laminated glass gets ready, they undergo through various stages. And 'Analysis' is the major and important stage in it. So in this work focus is given on the analysis of laminated glass by conventional FEA method and non-local peridynamic simulation.Due to their wide applications and comparatively less cost laminated glass is used in many areas. In order to design a good, laminated glass for safety purpose, the damage and fracture occurring in it due to impact load should be predicted.

Classical continuum mechanics is the basic approach to calculate the deformation and then further terms like stress, strain etc. The software LS DYNA uses the same concept as a program behind the card MAT_32 which is used for the analysis of the laminated glass. But as it uses differential equations which can't be applied for cracks, the program is

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modified by introducing integro-differential equations known as peridynamic equations. And same peridynamic control card can be used to analyze the fracture in the laminated glass.

1.1 Glass

Usually, soda lime glass is used to prepare LG, which is produced by float process and heat treated by annealing process. The main advantage of using annealed glass is residual stresses are very less into this. This makes easy cutting of glass layers.

1. 2 Polyvinyl Butyra (PVB)

This is the most widely used interlayer in the LG. PVB material is the chain of polymers and it is a kind of thermoplastic. Thermoplastic is a plastic which melts upon heating and can be reused. The PVB polymer is a long chain of monomers which are bonded each other by the Van-der-wall bond. The structure of PVB is like boiled noodles which are difficult to separate as they are placed randomly. The Figure 1 shows structure of PVB.

Fig.1 Structure of PVB

II. EXPERIMENTAL SETUP

In this kind of test the laminated glass is simply supported on the supports and then a ball of known mass and density is made to fall on it from certain known height. As the glass gets fractured the types of cracks can be viewed by naked eyes. And then conclusion can be drawn from it. While performing free fall test on the laminated glass, the safety laminated glass specimen of dimensions 300mm X 300mm X 6mm is kept on the four rectangular mild steel metal pieces whose dimensions are 50mm X 30mm X 6mm as shown in figure 2. The metal pieces act as four simply supports at four corners A, B, C and D. The backing plate is not provided behind the glass to capture the real behavior of glass. Now the solid steel ball of 0.5kg mass and 50mm diameter is dropped from the height of 150mm on the glass, as a result of it the glass did not break. Then the height of ball is raised to 300mm and dropped on a laminated glass. As the result of it the glass got fractured and cracks were observed.

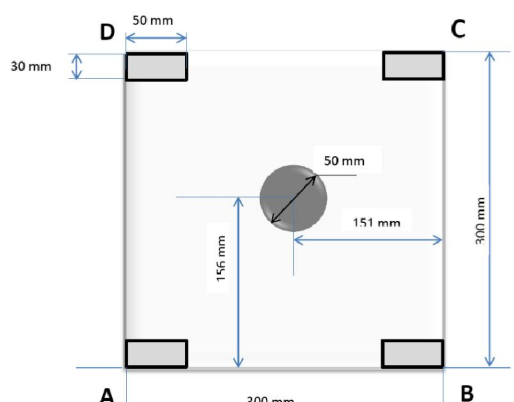

Fig.2Non-instrumented Impact Test Setup

2.1 Results of Experiment

When the experiment is performed the cracks originated at the center and ended at the end of the plate as shown in the figure 3. Branching was not there in any of the crack. And as the glass contains polymer layer in between, there was change in material and hence crack did not propagate further and lost its energy by transferring the impact energy to the PVB interlaying material. Top layer of glass is brittle in nature so it broke but the PVB layer is ductile in nature so it deformed slightly but did not damage. The PVB interlayer has strong binding properties so it holds the fractured glass on it without losing any particles. And as a result the bottom layer was totally safe and no crack was observed in it.

According to energy criteria fracture occurs when energy available for crack growth is sufficiently high to overcome the resistance of material. The material resistance may include the surface energy, plastic work or other type of energy dissipation associated with propagating crack. The K.E.induced was 1.50J after impacting a ball of mass 0.5kg from the height of 300mm.

A material is said to cleave when it breaks under normal stress and fracture path is perpendicular to the applied stress. That is cracks are perpendicular to the direction of applied load and parallel to surface of plate. This process involves separation of atoms along the direction of applied stress.It is assumed that all atoms separate simultaneously once their separation reaches critical value. A material fractures when sufficient stress and work are applied at the atomic level to break the bonds that hold atoms together. The bond strength is supplied by the attractive forces between the atoms.The equilibrium spacing occurs where the potential energy is minimum. A force is required to increase the separation distance from the equilibrium value. This force must exceed the cohesive force to sustain the bond completely. Theoretical cohesive strength or ideal strength necessary to break the bond is given by the equation.

$$\sigma_c = \sqrt{\frac{E_g \gamma_s}{x_0}}$$

According to [6] if γ_s=3J/m2, x_0= 0.2nm, Eg=70GPa then σ_c= 32.40 GPa

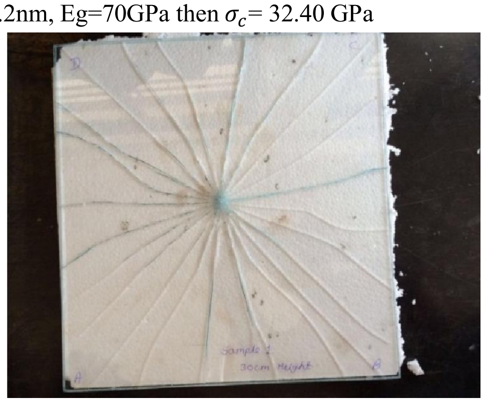

Fig 3 Fractured view of glass

III. PERIDYNAMICS

There is problem with classical continuum mechanics approach in dealing with discontinuous material. So the peridynamics, a non-local continuum mechanics approach is the best choice to analyze the problems with discontinuity. The peridynamic formulation of continuum mechanics was introduced by Silling (2000) in order to extend the classical continuum formulation to problems that involve discontinuities, such as cracks.

Peridynamics is a Greek word which can be split as peri and dyna. Peri means near and dyna means force. That is, it is the study of forces of points separated by finite distances as in case of cracks or brittle fracture. It is a non-local failure theory where failure criteria depends on the state of the material within a radius of influence which surrounds the integration point as shown in figure 4. Without non local criteria strains will tend to localize randomly with mesh

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refinement leading to results which can change from mesh to mesh. In peridynamics differential equations from classical continuum mechanics are replaced by integro- differential equations.

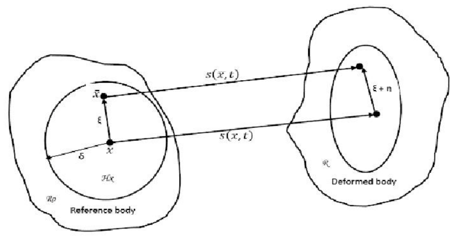

Fig. 4 Principle of Peridynamics

Let Ro be the reference body and R be the deformed body. Let x be the point of interest and x’ be the neighboring point of it. On applying force they will get displace to new positions by a distance s(x,t) and s(x’,t) respectively. Each point of consideration is surrounded by the number of points around it. And the effective interacting distance of a point and its neighbor is region where particles exerts force on each other is known as the horizon size Hx of radius δ around a point x. The peridynamic formulation uses integration of nodal forces instead of using differential equation of motions.

The peridynamic equation of motion at point x and at a time t is given by

[6]

$$\rho\ddot{s}(x,t) = \int_{Hx} f(s(\overline{x},t) - s(x,t), \overline{x} - x)\, d\overline{x} + b(x,t)$$

IV. SIMULATION RESULTS

In the process of simulation the product is well defined with all the boundary conditions and analysis is carried to validate the product. In this project simulation results are plotted for the single layered glass using MAT_32 material model and the Peridynamic model. Later Peridynamic simulations are extended to the multi-layered glass (Laminated glass). And the results are plotted.

4.1 Single Layered Glass Model with Local FEA Method

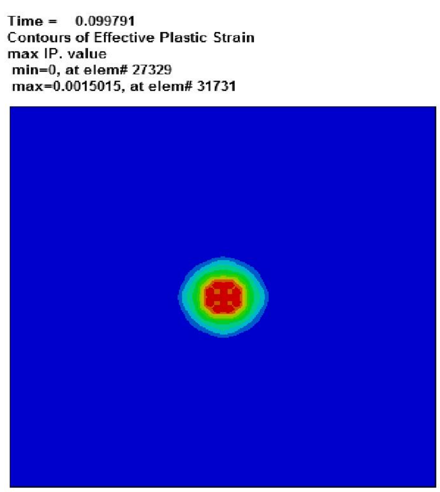

Fig 5(a)

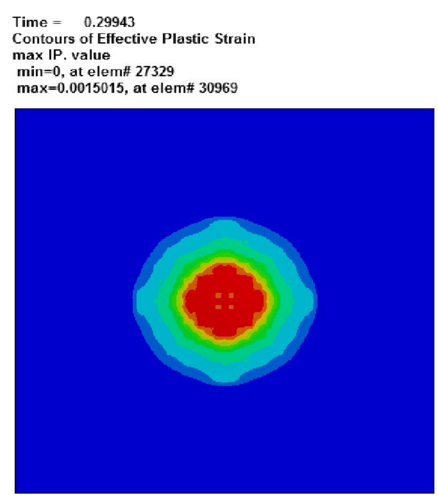

Fig 5(b)

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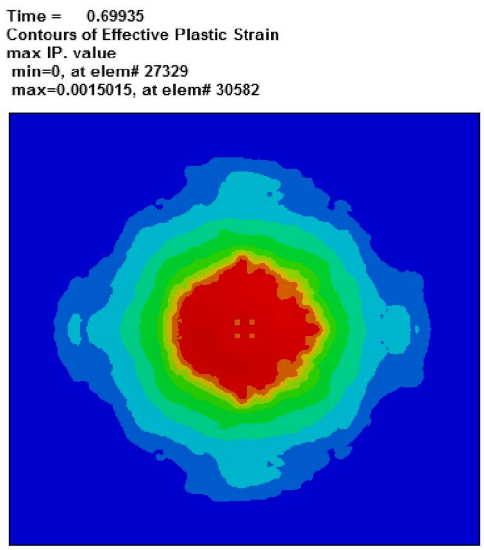

Fig 5(c)

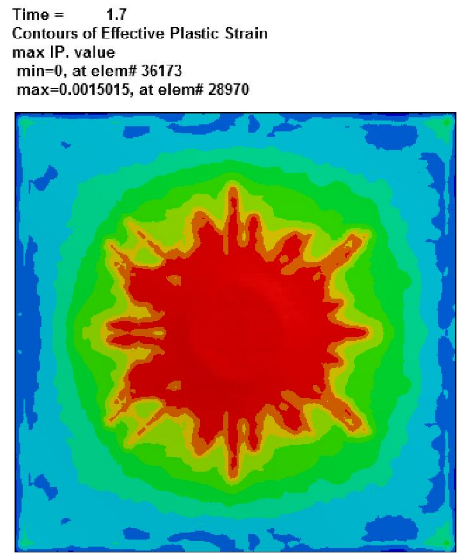

Fig 5(d)

Fig 5 Effective plastic strains at the time of 0.099791mS (Fig 5a), 0.29943mS (Fig 5b), 0.69935mS (Fig 5c) and 1.7mS (Fig 5d)

4.2 Single Layered Glass Model with Non-Local Peridynamics Method

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*SECTION_SOLID_PERI
$#     secid      elform          aet
           3          48
$         dr       ptype       IDILA        IDIM         IMF        EORC        GORS          IC
        0.80           0           0           8           0          60           0           0
$
*MAT_ELASTIC_PERI
$#       mid          ro         c/E         S/G
           1    2.240E-6    72.0E+09     8.0E+0
```

Fig 6 Perdynamic Control card

When results are plotted, as the glass is brittle but micro elastic material, it deflected only to the 3.9mm forming crack in the glass. The coarse mesh of mesh size 5mm is done as shown in the figure 7 given bellow.

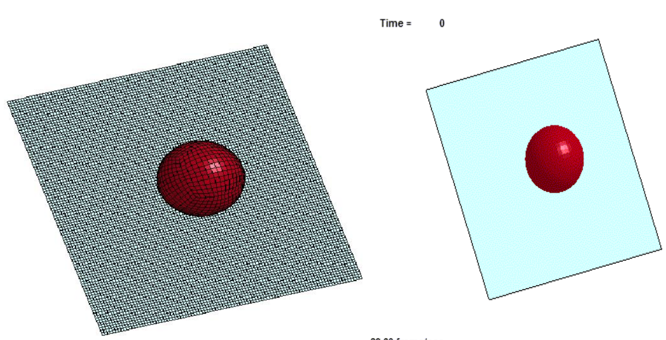

Fig 7 Coarse mesh of Glass

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The results obtained are as shown in figure 8.

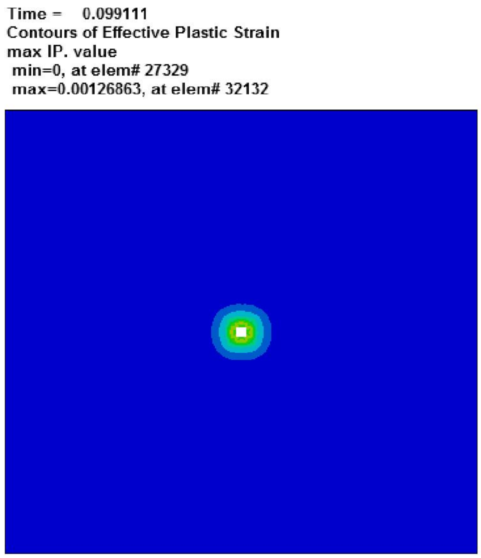

Fig 8(a)

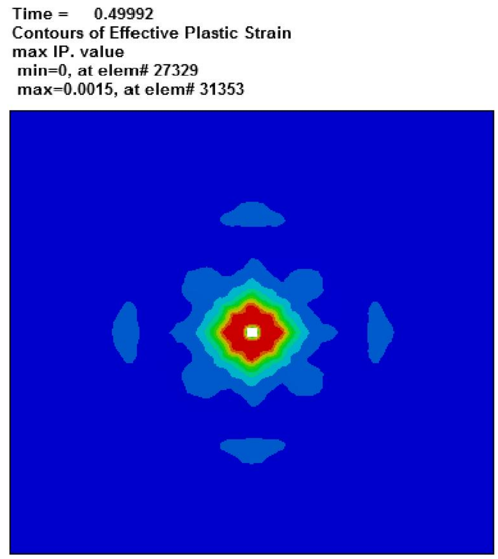

Fig 8(b)

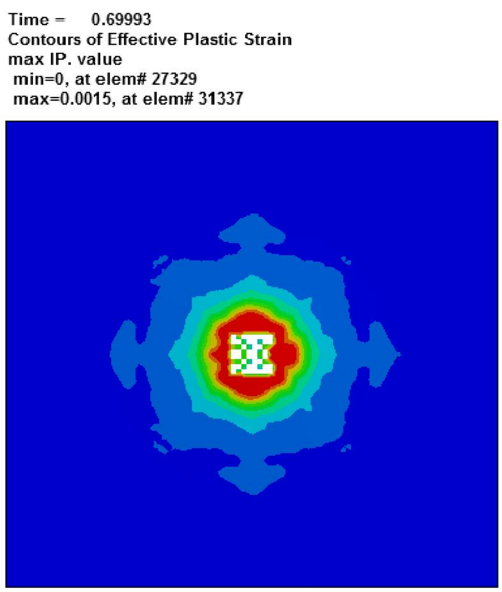

Fig 8(c)

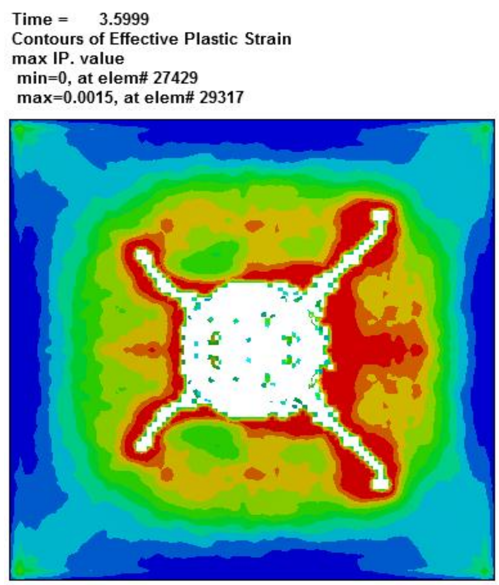

Fig 8(d)

Fig. 8 Effective plastic strains at the time of 0.099111mS (Fig 8a), 0.49992mS (Fig 8b), 0.69993mS (Fig 8d) and 3.599mS (Fig 8d)

When compared both the models, problems arrived in conventional local FEA method are resolved as we see displacement of glass is reduced by 62 % in the Peridynamics and crack is observed with same maximum strain of 0.15 %.

4.3 Laminated Glass Model with Non-Local Peridynamics Method

From the experiment test the distance of impact point is measured from all the sides of the glass. Also for the height of 300mm, velocity is calculated by considering the value of 1g acceleration as the ball is falling freely in downward direction.

$$v=\sqrt{2gh}=\sqrt{2*9.81*0.3}=2.42m/s$$

And same velocity is given in the software too.

The properties of glass, PVB interlayer and the rigid ball are assigned to the geometry in the peridynamic control card.

Table 1 Mechanical Properties

Glass Material:	PVB Material:
Density: 2440kg/m3	Density: 950kg/m3
Young's Modulus: 72 Gpa	Young's Modulus: 1.44 Gpa
Flexural Strength : 30 Gpa	Poisonous Ratio : 0.45
Poisonous Ratio : 0.2	Shear Modulus : 4 Gpa
Shear Modulus : 26.34 Gpa	
Energy Release Rate : 8.0J/m2	

Following figures 9 illustrate the crack propagation in the laminated glass at different time intervals. Mesh size is 2mm to 3mm.

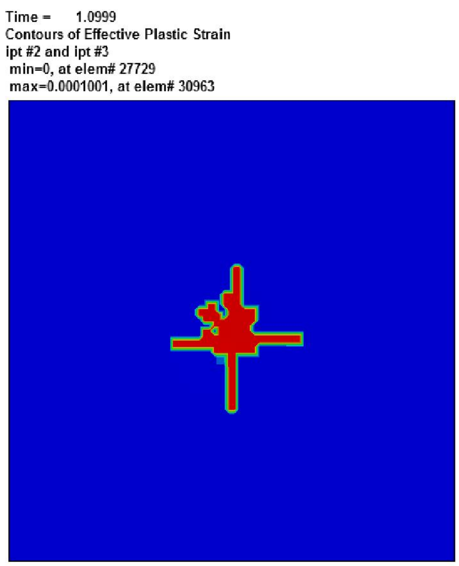

Fig 9(a)

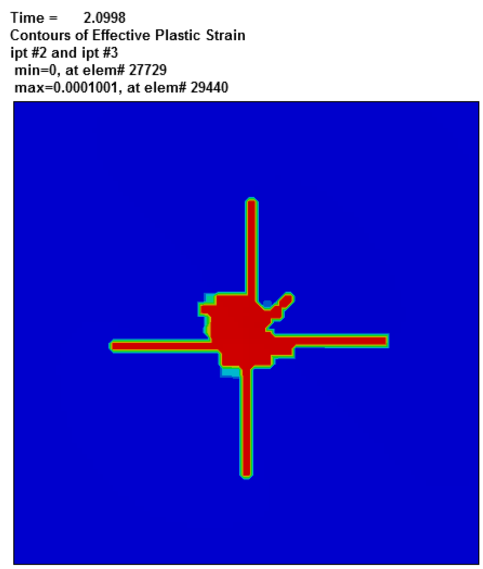

Fig 9(b)

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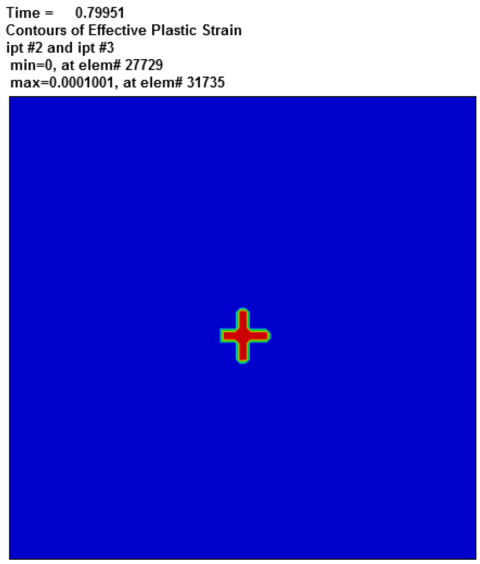

Fig 9(c)

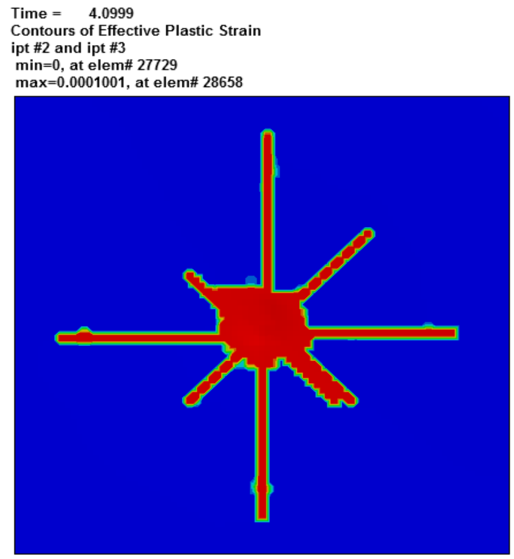

Fig 9(d)

Fig 9 Effective plastic strains at the time of 0.79915S (Fig 9a), 1.099mS (Fig 9b), 2.0998mS (Fig 9c) and 4.0999mS (Fig 9d)

The maximum impact velocity was 2.4m/s.The kinetic energy against time graph with maximum KE=1.45m/s was observed in the figure 10.

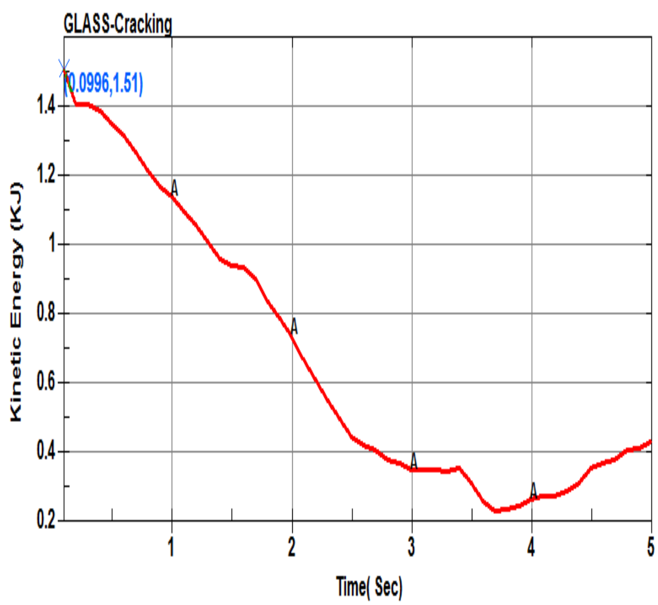

Fig 10 KE Vs Time

The internal energy against time is plotted as shown in the figure 11. Two internal energies for layer 1 and layer 2 of glass.

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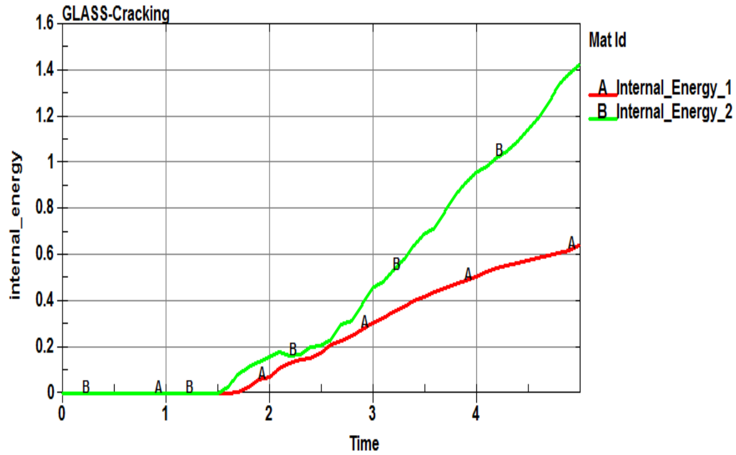

Fig 11 Internal Energy against Time

V. VALIDATION

5.1 Experimental Test

When free fall test on the laminated glass is performed, the observed cracks were propagating only through the upper layer of glass and crack depth was observed to be 3mm. All the cracks were originated from the point of impact and terminated to the end of the plate. The 8 major cracks were found along four edges and along four corners of the glass. And bottom layer of the glass was unaffected.

5.2 Simulation Results

After carrying simulations using Peridynamic control card for laminated glass, the obtained results were like proper crack propagation was observed for the mesh size 3mm. And same like experiments the eight major cracks were found along the eight directions of the edges and corners of the plate. The kinetic energy of 1.5J was observed by the calculation and 1.45J by that of the graph. The obtained displacement is also 0.8mm which is very less as occurs in brittle material. The maximum crack length observed was 138.84mm and the diameter of fractured area was 60mm as shown in the figure 12.

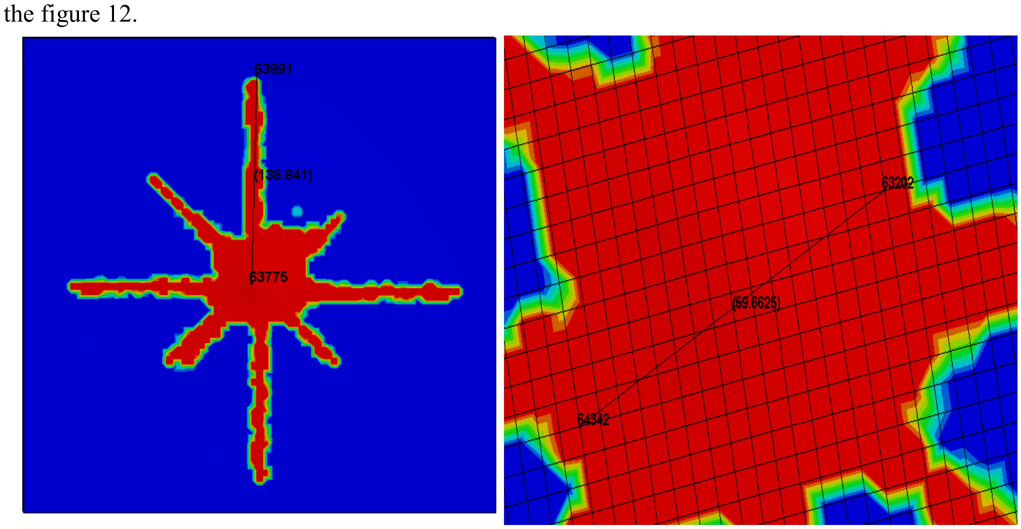

Fig 12 Maximum Crack Length and Fractured Area

The figure 13 shows the correlation of cracks from experiment test and the simulation result.

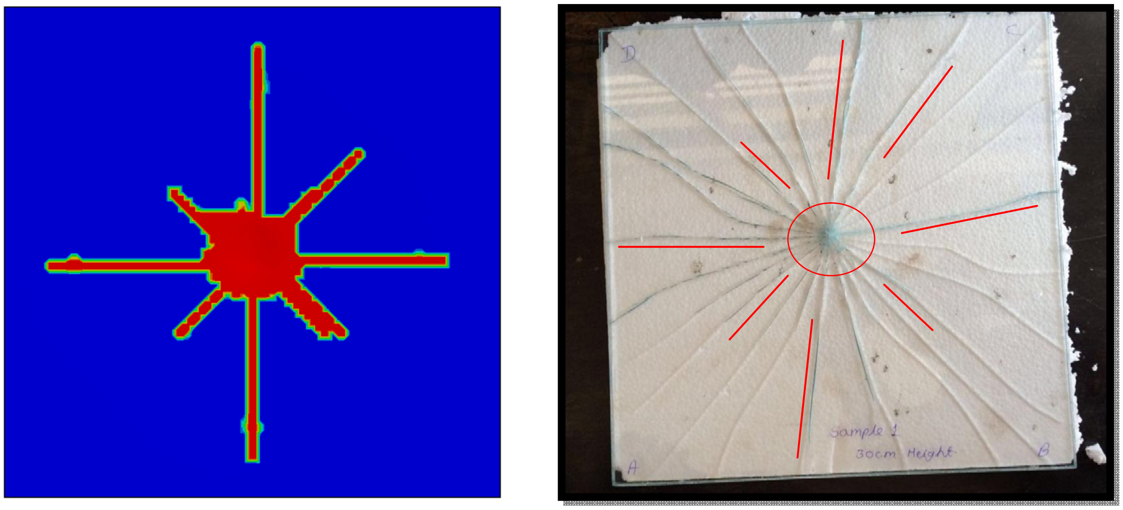

Fig 13 Correlation of the experiment and simulation results

VI. CONCLUSION

Free fall impact on a multilayer laminated glass system produces various kind of damages based on the height of impact, weight of impact, and position of the impact. Result of the experiments and results of the simulations are matching in terms of origin of crack and propagation direction. Though all the small cracks did not capture by the simulation, the major cracks can predict the damage morphology in the laminated glass. This is because the analysis is carried in the trial version of the software as the new version is going to launch in august 2016. The kinetic energy of 1.5J was observed in the theoretical calculations and 1.45J with the simulation results. The sectional force also ranges from 3N to 6N in the simulation, whereas in the calculation it shows the force of 4.9N.

When the glass gets manufacture, it undergoes from the various cycles and simulation is the important step. As comparing the results mentioned above we can say that the Peridynamics technique gives the more accurate result as compared to the conventional local continuum mechanics approach. So using the Peridynamics technique cost saving can be done at the earlier stages of manufacturing. Hence Peridynamics technique proves to be the best technique to analyze the brittle fracture.

In future the analysis can be continued to analyze bullet resistant glass, ceramics and other brittle material where crack is observed. The small cracks can also be captured by varying the element size and element type.

REFERENCES

[1]. Florin Bobaru, Wenke Hu, “The Meaning, Selection, and Use of the Peridynamic Horizon and Its Relation to Crack Branching in Brittle Materials” International Journal of Fracture 176 (2012), pp. 215–222; doi: 10.1007/s10704-012-9725-z.

[2]. Krishan Kumar, IshuMonga, “An Evaluation of Energy Absorption by Bullet Resistant Glass and its Mechanical Properties” International Journal for Research in Applied Science and Technology, Vol. 2 Issue VIII, August 2014 ISSN: 2321-9653.

[3]. Yongki An, Byung Yun Joo, Dong-Teak Chung and Se-Young Choi, “Finite element simulation of brittle fracture of bulletproof glass system” Journal of Mechanical Science and Technology 28 (1) (2014) 73~80.

[4]. F. Plassard, J. Mespoulet, P. Hereil, “Hypervelocity impact of aluminium sphere against aluminium plate: experiment and LS-DYNA correlation” 8th European LS-DYNA Users Conference, Strasbourg - May 2011.

[5]. ArashRamezani, HendrikRothe, “Investigation of Solver Technologies for the Simulation of Brittle Materials” The Sixth International Conference on Advances in System Simulation, ISBN: 978-1-61208-371-1.

[6]. Wenke Hu , Yenan Wang , Jian Yu , Chian-Fong Yen , Florin Bobaru, “Impact damage on a thin glass plate with a thin polycarbonate backing” International Journal of Impact Engineering, 62 (2013) 152e165

[7]. Mr. SatishRamavat, Mr. DevidasThorat, Mr. Prashant C., “Simulation of Bullet Impact on Bullet Resistant Steel Plate” HTC 2012, Godrej

[8]. Rabinder Singh Bharj, Sandeep Kumar, “The Effect of Size, Thickness, and Type of the

[9]. Bonding Interlayer on Bullet Proof Glass as per EN 1063”, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering Vol:8, No:2, 2014

[10]. DaeSikJung , Kook Chan Ahn, “Response of Monolithic and Laminated Glass under Impact Loading” International Journal of Engineering & Technology IJET-IJENS Vol:15 No:02

[11]. Wenyang Liu, “Discretized Bond-Based PeridynamicsFor Solid Mechanics” A DissertationSubmitted to Michigan State University, 2012