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Predictive Analysis of Laminated Glass Performance Under Static and Dynamic Loading Conditions

Amit Kumar Gupta [a], Yijian Lin [b], Steven Pesek [b], Nolan McDougal [b], Rosalyn Kent [b], Laura Dietsche [b]

a The Dow Chemical Company, Germany, agupta35@dow.com
b The Dow Chemical Company, USA

Abstract

Laminated safety glass is normally used when there is a possibility of human impact or where the glass could fall if shattered. Glass laminate films, the plastic film called an interlayer that is adhered between sheets of glass, are an important component of many glass applications. In an event that causes breakage of the glass, it is held in place by an interlayer, between its two or more layers of glass. The interlayer keeps the glass bonded even when broken, and its high strength prevents the glass from breaking up into large sharp pieces. Various physical tests (standard/non-standard) can be found in the literature to develop and screen the different interlayer materials. In the last several years, we have witnessed extensive growth in computational modeling of complex nonlinear behavior of laminated glass panels with viscoelastic interlayers. To evaluate the mechanical behavior of laterally-loaded interlayer in laminated safety glass, finite element (FE) modeling is widely used in industry. Recently, FE modeling techniques and methods helped to identify selection criterion for proposed materials to be used in the interlayer of laminated glass. The present study aims to develop a numerical model (Finite Element model) verified by experimental results/data given in literature and to utilize the model to examine the mechanical behavior of laterally-loaded interlayer films in laminated safety glass subjected to standard/non-standard tests (four-point bending test and Impact test) conditions. Also, parametric studies (effect of interlayer/glass thickness, impactor speed, soft/stiff interlayer material etc.) are performed through FE analysis to investigate the impact of these parameters on the behavior of the interlayer material.

Keywords

Laminated safety glass, finite element analysis, interlayer material, four-point bending test, ball impact/drop test, interlayer/glass thickness, impactor speed, crack propagation profile, soft/stiff interlayer material, Displacement-Velocity-Acceleration of impactor, ABAQUS, LS-DYNA

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1. Introduction

In general, glass can be classified by its fracture behavior. Conventional float glass, which is usually applied for windows, has sharp and large splinters and cannot be used as safety glass. If float glass is tempered, the fragments are small and blunt and it can be used as safety glass. The basic construction of laminated glass, e.g., a windscreen, involves two pieces of float glass together with an interlayer. Laminated glass, also known as laminated safety glass (LSG), is composed out of two or more glass panes bonded by one or more interlayers. Most laminated glass interlayer materials are made of polyvinyl butyral (PVB) and, ethylene-vinyl acetate (EVA) (Dural et al. 2020; Martín et al. 2020; Zemanova et al. 2022). Several researchers have made efforts towards developing alternative materials, mainly based on thermoplastic polyurethane (TPU), polymethyl methacrylate (PMMA), polyethylene terephthalate (PET), polycarbonate (PC), and others. The interlayer film bonds the two exterior glass panes together and creates the laminate represented by Figure 1.

Fig. 1: Composition of laminated glass.

Fracture of plain glass can occur without any warning, with very little deformation, and in a split second. Due to this brittle behavior and the associated risks concerning safety, it cannot be used for these kinds of applications. In contrast to plain glass, laminated glass does not disintegrate upon fracture, but the glass shards are kept together by the interlayer, preventing them from harming bystanders. Hence the material has residual load-bearing capacity and, thus, the necessary redundancy for structural use.

Laminated glass has been increasingly employed for impact resistant glass applications in automotive, aerospace, and civil industries. The reason for the popularity is that it combines the strength and transparency of the glass with the safety of the laminating film. It makes glass structure resistant after failure.

Laminated safety glass (LSG) has benefits beyond structural integrity as the interlayer can contribute to additional comfort and architectural properties. It has very good acoustic and thermal properties and can be used for structural support purposes. A few examples are acoustic insulation, thermal insulation, UV-blocking properties, tinted glass, and smart glass. Today, the most common use for LSG is situated in the automobile industry for the production of windshields. But it has many other applications such as bulletproof glass, greenhouses, skylights, structural elements, balustrades, burglary-resistance glass, hurricane-resistant glass, and blast-resistant glass. In order to improve the current technology, in-depth research is necessary to understand how LSG responds under air blast loading and by which parameters it is affected.

The mechanical performance of interlayer materials and Finite Element modeling (FEM) of laminated glass assemblies has been largely studied (Pelfrene et al. 2016; Fourton et al. 2020; Teotia et al. 2018). Influencing parameters have been investigated in order to gain knowledge of interlayer behavior with respect to adhesion of the interlayer (Aggromito et al. 2022), stiffness of the interlayer, thickness of the interlayer, thickness of the outer glass panes, and impact velocity. Various physical tests (standard/non-standard) to develop and screen the different interlayer materials can be found in the literature (Barredo et al. 2010; Prasongngen et al. 2009; Zemanova et al. 2022). Information is readily available for PVB, which has been a consolidated interlayer for many years.

There is currently a need for further research on alternative interlayer materials in order have better understanding of how they behave in laminated glass assemblies, and how they respond when subjected to different static and dynamic loading scenarios, working temperatures and aging factors.

Evaluation of different interlayer material can be done by application testing or finite element simulation. The target is to use finite element (FE) simulation to accelerate decision making at the early stage of material development. Predictive modeling and parametric studies will help identify selection criterion for new materials to be used in the interlayer of laminated glass.

In this study, a detailed literature search was conducted to know more about laminated safety glass, different types of interlayer materials, interlayer mechanical behavior, interlayer evaluation testing methods (static and dynamic), and the effect of influencing parameters (interlayer/glass thickness, impact speed etc.) on laminated glass during static and dynamic load cases to predict the performance ranking of interlayer materials. This information will be used to develop numerical (FE) model based on static and dynamic loading to predict the mechanical behavior of laminated safety glass in different glass/interlayer configurations. In addition, a parametric study will be conducted to predict the performance of an interlayer material in different configurations (impact speed, soft interlayer, stiff interlayer etc.) to meet the needs of the application.

1.1. Theoretical Concept of Laminated Glass

In short-time dynamics, the elastic behavior for small deformations of the composite is determined by the glass. For large deformations, the PVB-interlayer plays a dominant role because the brittle glass cannot withstand large strains: the glass layers fail and the PVB-interlayer still has a load-carrying capacity left which can be observed experimentally. One situation in which this behavior may be expected is the response of a car windshield, following a roof crash, over-roll or a cork-screw flight event (Du Bois et al. 2003). Thus, we have to consider two extreme cases: the glass fails or it does not fail. If the glass fails, only the interlayer (reinforced with some splinters of glass) has a load-carrying capacity left (Timmel et al. 2007).

Glass itself does not have any ductility, so upon its failure it immediately disintegrates. But in most cases the laminated structural element may have some residual load-bearing capacity, as the laminating film prevents disintegration and ensures locking between the glass particles. The failure process of laminated glass plates has three phases, as shown in Figure 2. The first stage is where both glass layers carry the load. The stress distribution for Stage 1 is illustrated on the left of Figure 2. At this stage the only load on the laminating film is from the shear stress.

As the second stage begins, the bottom glass plate – (tensioned part in Figure 2) breaks, when it can no longer carry the load. The stress distribution in the upper plate becomes symmetrical, the stress value being the same on both edges. In this stage the laminate can carry less load, (its stiffness is decreased,) but it is capable of resisting more deflection. In the third stage the upper glass plate fails, so the stress balance of the cross-section is only held together by the tensile strength of the PVB film. Due to the locking between the particles in the upper glass plate it can withstand compression, so the cross-section maintains its equilibrium (Molnar et al. 2012).

From the mechanical point of view, an interlayer and laminated glass plates are behaving differently. To define the extra load bearing capacity caused by the interaction of the interlayer is a continuing challenge (Molnar et al. 2012).

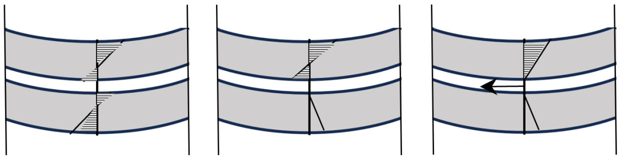


Fig. 2: Theoretical Theoretical failure stages (stages 1 - left, stage 2 -middle, stage 3 – right) in laminated glass.

1.2. Internal Performance Requirement Set in Static and Dynamic Loading Conditions

The following general requirements for the static and dynamic load-cases are expected:

Static load case: Both maximum load and displacement value of simulation should be with-in 10-15 % of given experimental values as mentioned in literature. In addition, simulation curve characteristics should close to the empirical curve characteristics.

Dynamic load case: Displacement value of numerical simulation should be with-in 10-15 % of given experimental values as mentioned in literature. In addition, acceleration and velocity simulation curve characteristics should be close to the empirical curve characteristics.

2. Experimental details as given in literature

2.1. Test #1: Static Loading Condition – Four-Point Bending Test

Based on literature data (Timmel et al. 2007), the following test details were adopted to predict the behavior of laminated glass. The laminated glass plate was loaded by two cylinders on the top surface for vertical loading and supported by two cylinders of similar diameter on the bottom surface of the glass. The fundamental aim of the experiment was to evaluate the behavior of laminated glass under slow displacement loading (quasi-static) and to validate the numerical (Finite Element) model.

Test setup details:

The experimental set-up consists of a laminated glass plate (length = 1100 mm, width = 600 mm, glass thickness = 3 mm and PVB interlayer thickness = 0.72 mm PVB) supported by two cylinders (diameter = 50 mm, distance = 1000 mm). The plate is loaded by two cylinders (diameter = 50 mm, distance = 200 mm) for which we increased the displacement slowly (quasi-static) up to 30 mm.

Material data:

PVB interlayer material properties (Density=1.1 e-9 tonnes/mm^3, Poisson Ratio= 0.435 and Engineering stress-strain curves) are obtained from literature (Timmel et al. 2007). Similarly, glass material properties (Density=2.2 e-9 tonnes/mm^3, Elastic modulus=70 e3 MPa, Poisson Ratio= 0.23 and failure strain = 0.15%) are obtained from the literature. Loading cylinders are assumed to have rigid or steel-like material properties (Density=7.86 e-9 tonnes/mm^3, Elastic modulus=210 e3 MPa, Poisson Ratio= 0.3).

Experimental output data:

The reaction force versus the prescribed displacement of the cylinder curve obtained in literature is shown in Figure 3. After a displacement of 20 mm, the glass fails and there is no contact left between the cylinders and the PVB. Therefore, the load carrying capacity of the PVB could not be checked by this test (Timmel et al. 2007).

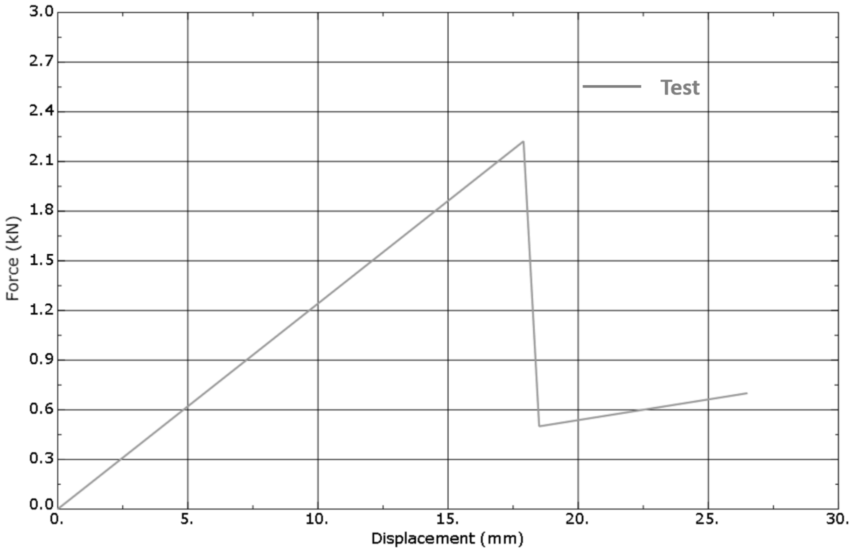


Fig. 3: Load-displacement curve as given in literature for Test#1: Four-point bending test.

2.2. Test #2: Static Loading Condition – Four-Point Bending Test

It is common to use multiple layers of film or thick film (0.38 mm, 0.76 mm, or 1.52 mm) to laminate the glass plates, as in most applications a single layer or thin layer is not safe, because after failure the PVB film plays a significant role in the resistance of the structural element. As per standard EN 1288-3:2000, a displacement driven by hydraulic load equipment was used, and the deflection at the middle of the board, and at supporting rolls was measured (Molnar et al. 2012).

Test setup details:

Laminated glass specimen has a setup size (1100 mm × 360 mm), but the thickness of the glass plates and the laminating film were varied in experiments. All laminates were symmetric, constructed with two identical glass layers and a PVB layer. Figure 4 shows the schematic diagram of the test setup as given in literature (Molnar et al. 2012).

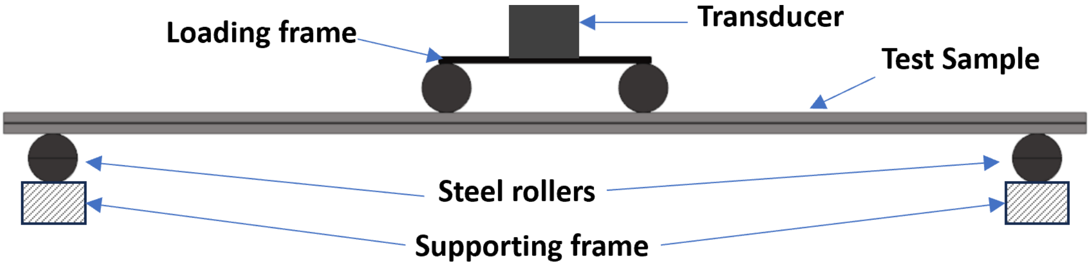


Fig. 4: Experimental setup and schematic diagram of Test#2: Four-point bending test.

Material data:

PVB interlayer material properties (Density=1.03 e-9 tonnes/mm^3, Poisson Ratio= 0.45 and Engineering stress-strain curves) are obtained from literature (Molnar et al. 2012). Similarly, glass material properties (Density=2.5 e-9 tonnes/mm^3, Elastic modulus=70 e3 MPa, Poisson Ratio= 0.22 and failure strain = 0.15%) are obtained from literature. Loading cylinder assumed to have rigid or steel-like material properties (Density=7.86 e-9 tonnes/mm^3, Elastic modulus=210 e3 MPa, Poisson Ratio= 0.3).

Experimental output data:

The deflection values of interlayer thickness in literature (Prasongngen et al. 2009) shown in Figure 5. The deflection is calculated using the middle deflection minus the deflections at the supports.

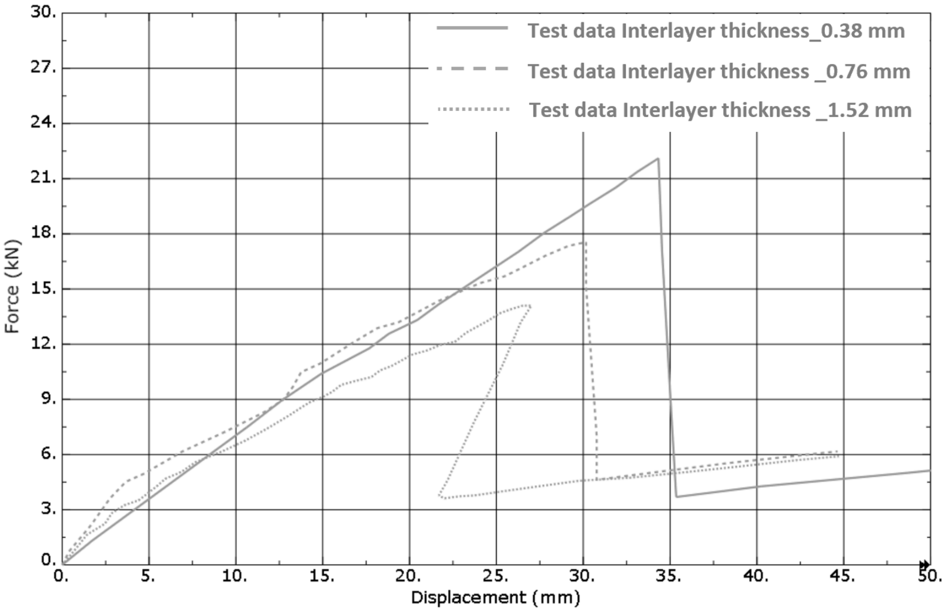


Fig. 5: Load-displacement curve as given in literature for Test#2: Four-point bending test.

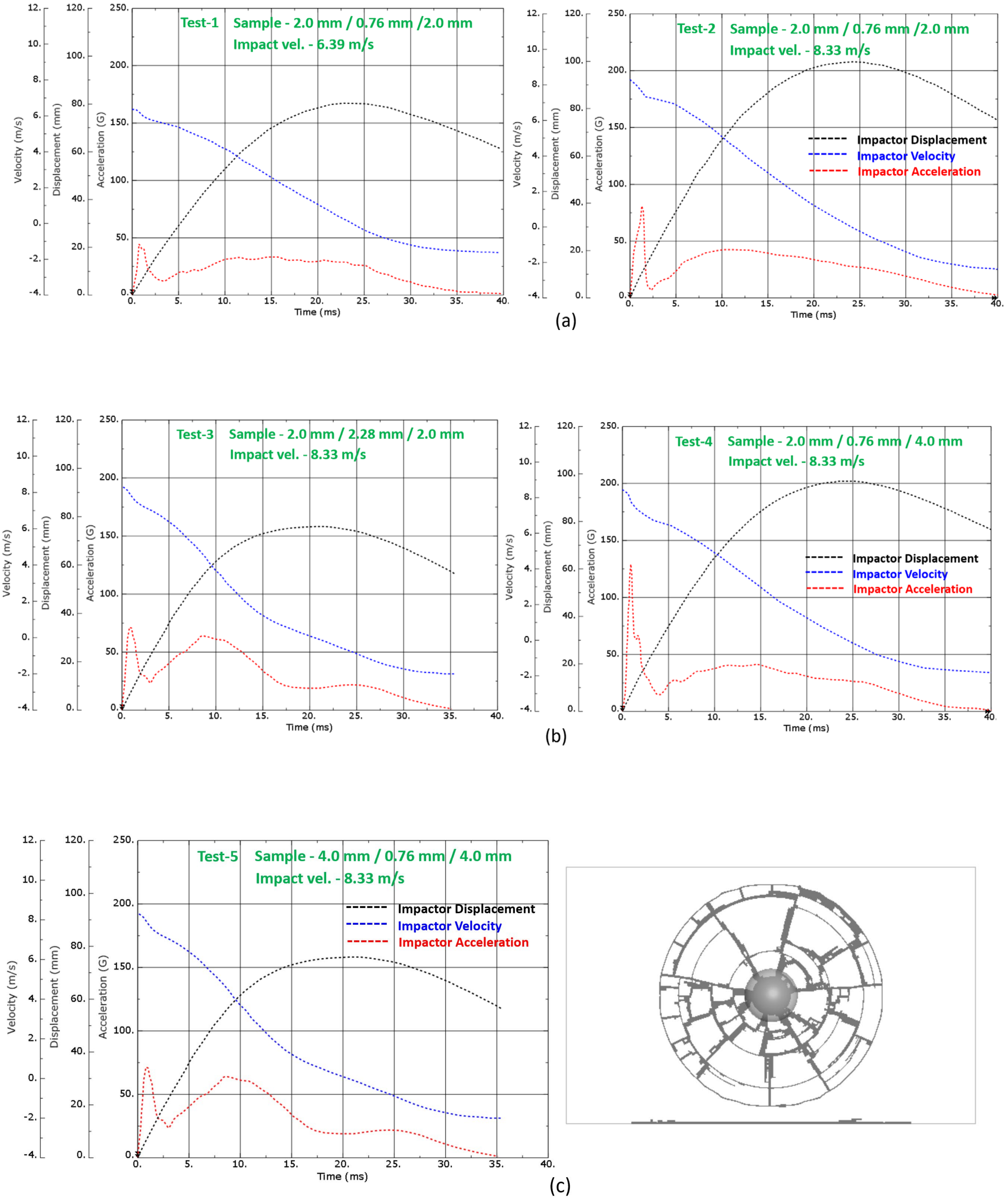
2.3. Test #3: Dynamic Loading Condition – Ball Drop/Impact Test

There are extensive experimental studies described within the literature on the dynamic response of laminated glass subjected to dynamic/impact loading. To investigate the dynamic behavior of laminated glass panel with PVB interlayer material, a series of experiments with low and high velocity impact cases were considered from the literature (Yuan et al. 2012). The current experiments focus on the effects of impact velocity, and laminate thickness (glass and interlayer) on performance. The predicted time-history of central displacement, velocity and acceleration are observed from the experiments.

Test setup details and experimental output:

The in-plane dimensions of the laminated glass panel are 1300 mm × 830 mm with a test area of 1260 mm × 790 mm. To study the influence of laminate thickness on panel response, the thickness of the glass layer – both outer (impact glass) and inner (non-impact glass) – varies from 2 mm to 4 mm, whereas the thickness of the interlayer ranges from 0.76 mm to 2.28 mm.

Experimental setup shown in literature (Yuan et al. 2012) represented through FE model to simulate the impact response of laminated glass. In an attempt to achieve fixed boundary conditions, the laminated glass was clamped by the rigid frame. The projectile was launched with different impact velocities ranging from 6.39 to 8.33 m/s. The projectile used for all the test was a EEVCWG17 headform impactor with radius of 82.5 mm and mass of 4.52 kg. The headform impactor is equipped with a three-dimensional acceleration sensor, which is used to obtain its time-history of displacement, velocity, acceleration, and approx. crack pattern as given in Figure 6 (a-c). The impact point was kept at the center of the laminated glass and the impact remains perpendicular to the surface of the outer glass layer.



(a)

(b)

(c)

Fig. 6 (a-c): Experimental time-history of displacement, velocity and acceleration in different test conditions.

Material data:

PVB interlayer material properties (Density=1.03 e-9 tonnes/mm^3, Poisson Ratio= 0.49 and Odgen strain energy function with mu= 0.0138039, alpha=2.58912) are obtained from literature. Similarly, glass material properties (Density=2.5 e-9 tonnes/mm^3, Elastic modulus=70 e3 MPa, Poisson Ratio= 0.23 and failure strain = 0.10%) are obtained from literature. Loading cylinder assumed to have rigid or steel-like material properties (Density=7.86 e-9 tonnes/mm^3, Elastic modulus=210 e3 MPa, Poisson Ratio= 0.3).

3. Numerical (Finite Element Analysis) Simulation

The Numerical simulation, or Finite Element Method (FEM), provides a versatile tool to predict both local and, global forces, deformations, and energy absorption in static and dynamic events. Other important factors, such as a cracking/damaging pattern of the glass, are possible to predict through simulation. The current numerical model approach, when combined with an understanding of the cracking/damaging of glass and the deformation of the PVB, can predict the failure of laminated glass subject to impact loading. A numerical model of laminated glass with PVB was developed and verified based on experimental results. An important goal in FE simulations is to have mesh-independent results. This is often achieved by optimizing an overall mesh density. However, mesh patterns and size gradients can also have an impact on simulation results. For validation of the finite element model, a four-point bending test and impact test were simulated and compared with experimental data as given in literature (Timmel et al. 2007; Molnar et al. 2012; Yuan et al. 2017).

3.1. Test #1: Static Loading Condition – Four-Point Bending Test

FE modelling, boundary condition and loading:

The glass layers and interlayer are modeled using three-dimensional solid elements in the FE model and solved with ABAQUS (Abaqus user manual 2022). The inner and outer glass layers, PVB interlayer and impactor are modeled as different parts in numerical simulation. In the numerical simulation, the glass layers are modelled with solid elements considering maximum strain at failure as erosion criterion, i.e., failed elements are deleted from further computation. The rubber-like behavior of the PVB can be modelled by using an hyperelastic material law. A rigid cylinder is modeled as a solid element with the material properties of steel. To perform large deformation analysis the ‘‘geometric nonlinearity’’ option is used. The bond between the interlayer and glass layer is assumed to be perfect with no debonding or slipping during impact.

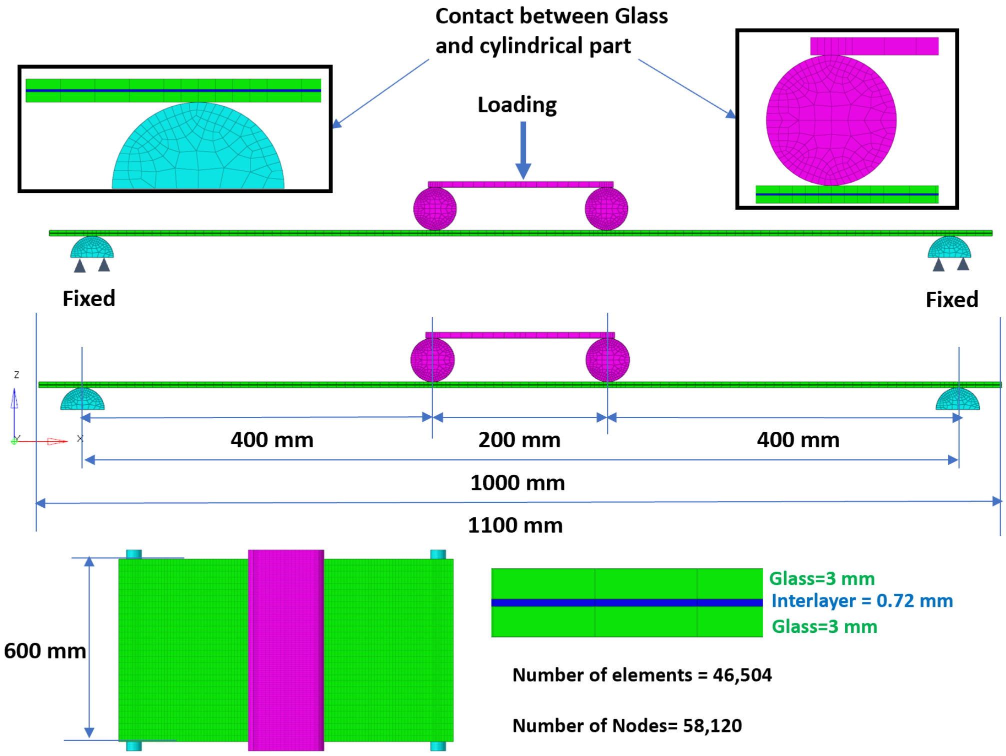


Fig. 7: FE model details, applied boundary conditions and loading as defined in Test#1.

For simulations of Test#1, the FE model details, applied boundary conditions and loading are shown in Figure 7, where the lower/supported cylinders are fixed in all X, Y, & Z direction and loading is applied on the upper cylinders. The contact between the rigid cylinders (upper and lower) and laminated glass are defined. For validation, the force and displacement of the upper cylinder has been measured in this test and compared to the numerical results.

3.2. Test #2: Static Loading Condition – Four-Point Bending Test

FE modelling, boundary condition and loading:

In Test#2 - simulations, a numerical (FE) model was developed with width of sample, interlayer and glass thickness (0.38 mm, 0.76 mm & 1.52 mm) as per test conditions, as given in literature (Molnar et al. 2012). The glass layers and interlayer are modeled using three-dimensional solid elements in FE model and solved with ABAQUS. The inner and outer glass layers, PVB interlayer, and impactor are modeled as different parts in numerical simulation. In the numerical simulation, the glass layers are modelled with solid elements considering maximum strain at failure as erosion criterion, i.e., failed elements are deleted from further computation. The rubber-like behavior of the PVB can be modelled by using an hyperelastic material law. Rigid cylinders are modeled as solid elements with material properties of steel. To perform large deformation analysis ‘‘geometric nonlinearity’’ option is used. The bond between the interlayer and glass layer is assumed to be perfect with no debonding or slipping during impact. For Test#2, FE model details, applied boundary conditions and loading are the same as above shown in Figure 7.

3.3. Test #3: Dynamic Loading Condition – Ball Drop/Impact Test

FE modelling, boundary condition and loading:

For Test#3 simulations, the glass layers and interlayer are modeled using three-dimensional solid elements in the FE model and solved with LS-DYNA (LS-DYNA keyword manual 2017). The coincident finite elements are used to model the deformable layered set-up of laminated glass: solid element with brittle failure for the glass components and solid elements to simulate the ultimate load carrying capacity of the PVB-interlayer. In the numerical simulation with the LS-DYNA, the glass layers are modelled with solid elements considering maximum strain at failure as erosion criterion, i.e., failed elements are deleted from further computation. *MAT_ADD_EROSON card is used with glass material card to predict the crack propagation. The inner and outer glass layers, PVB interlayer and impactor are modeled as different parts in the numerical simulation. The bond between the interlayer and glass plies is assumed to be perfect with no debonding or slipping during impact. The boundary conditions are shown in Figure 8. The outer edges of the laminated glass are fixed in all X, Y & Z direction and an initial velocity is applied on the impactor ball. The contact between rigid ball and laminated glass is defined. For validation, the displacement, velocity, and acceleration of the rigid ball is measured in this test and is compared to the numerical results.

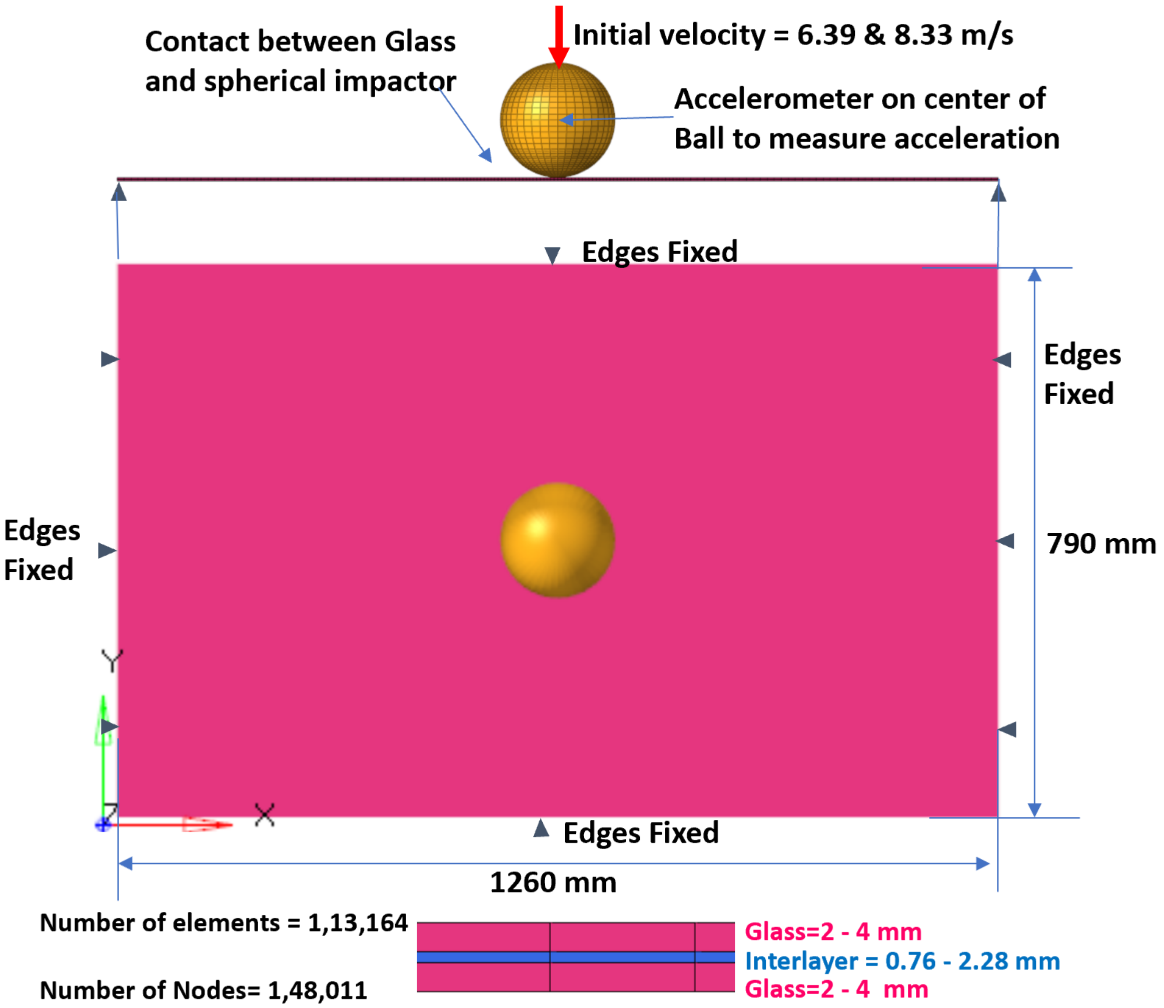


Fig. 8: FE model details, applied boundary conditions and initial velocity as defined in Impact test.

4. Results and Discussion

4.1. Test #1: Static Loading Condition – Four-Point Bending Test

The load deflection of the cylinder has been obtained from the simulation and compared to the experimental results as shown in Figure 9. It was observed that the Test#1-Four-point bending simulation result (peak force and maximum displacement) are able to closely (<10-15%) predict experimental result. The overall simulation curve characteristic is similar to the experimental curve.

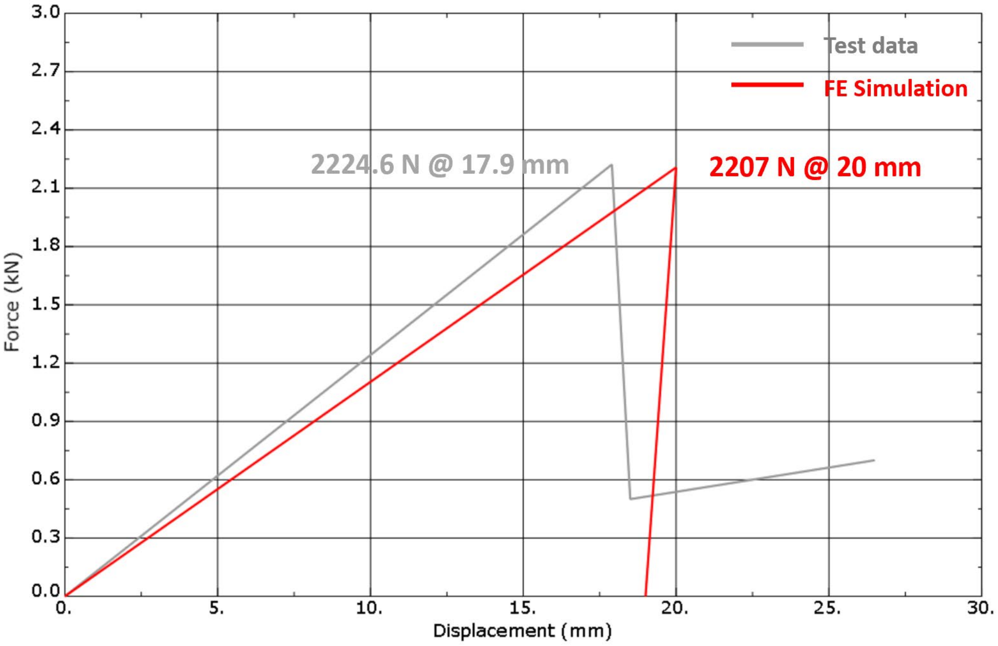


Fig. 9: Simulation-experimental correlation of Test#1: Four-point bending test.

4.2. Test #2: Static Loading Condition – Four-Point Bending Test

The load-deflection of the cylinder has been obtained from the simulation and compared to the experimental results as shown in Figure 10 for all interlayer thickness. It was observed that simulation curve characteristics are similar to the experimental curve. It was also observed that an increase of the thickness of the interlayer results in a decrease of the bending stiffness of the structure.

Table 1: Simulation results of four-point bending test with different interlayer thickness.

Glass Thickness top/bottom	Interlayer Thickness	Experiment output	Experiment output	Simulation output	Simulation output	% difference simulation w.r.t. experiment	% difference simulation w.r.t. experiment
mm	mm	Force [kN]	Displacement [mm]	Force [kN]	Displacement [mm]	Force [kN]	Displacement [mm]
10 / 10	0.38	22.11	34.33	22.33	33.30	1.0	3.0
10 / 10	0.76	17.55	30.16	18.05	29.0	2.85	3.84
10 / 10	1.52	14.10	27.01	14.73	26.0	4.45	3.73

Table 1 shows that the experimental and simulation variation in maximum force and displacement condition are under 10-15 %. Further analysis of the load-deflection data shown in Figure 10 indicates that the maximum value of displacement is a decreasing function of the PVB thickness with a cubic polynomial relationship. It is confirmed by the experimental and numerical comparison that the effective rigidity of the structural element is decreased by increasing the thickness of the PVB.

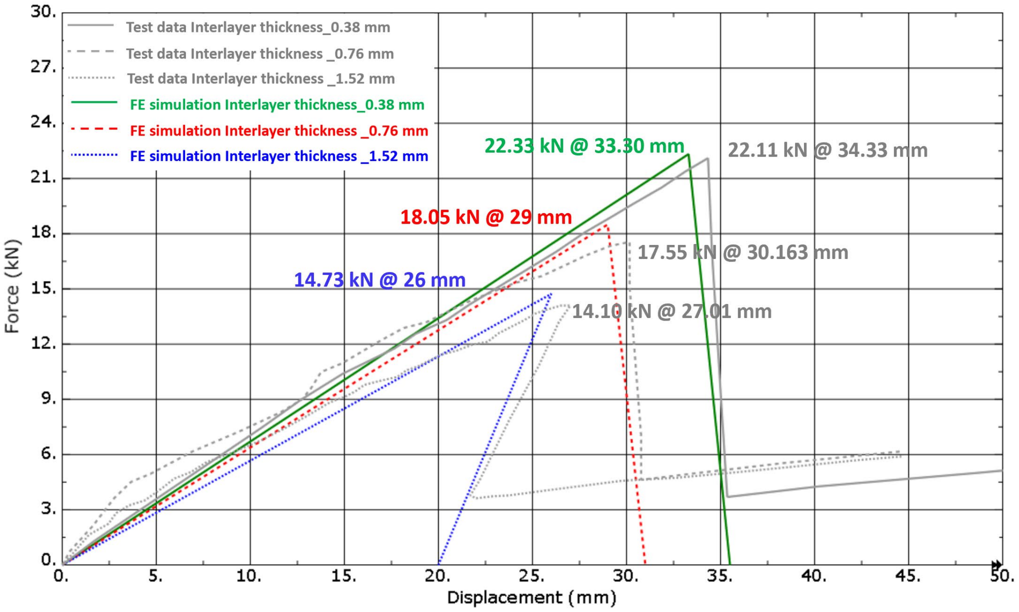


Fig. 10: Simulation-experimental correlation of Test#2: Four-point bending test.

4.3. Test #3: Dynamic Loading Condition – Ball Drop/Impact Test

For the ball impact/drop test cases, numerical model predictions and experimental results are compared to validate the numerical model. After glass impacted by impactor, radial cracks developed on the laminated glass and damage or fracture of interlayer indicated complete loss of load carrying capacity of laminated glass, or all the stress components drop to zero. Below is the simulation-experimental correlation under different test conditions.

Test#1– glass-interlayer-glass configuration (2 mm glass/ 0.76 mm interlayer/ 2 mm glass), impact velocity 6.39 m/s:

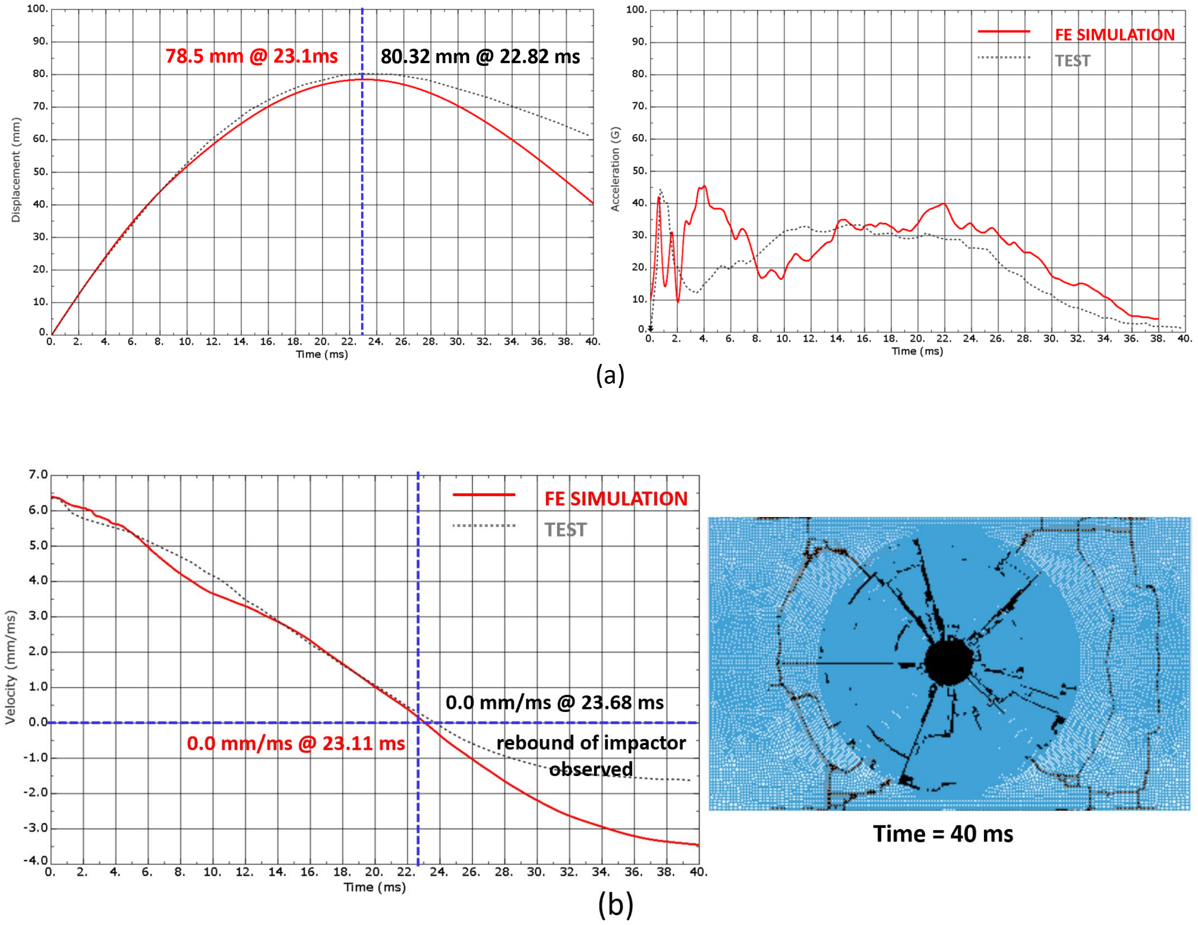
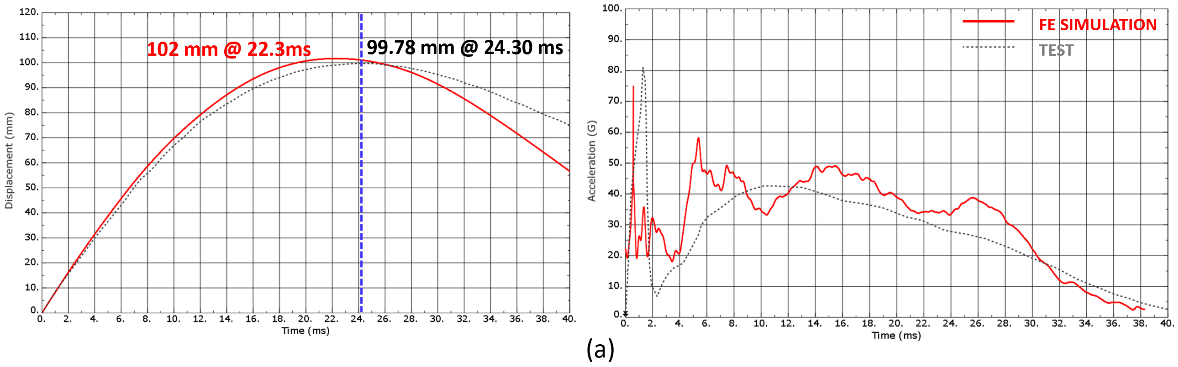


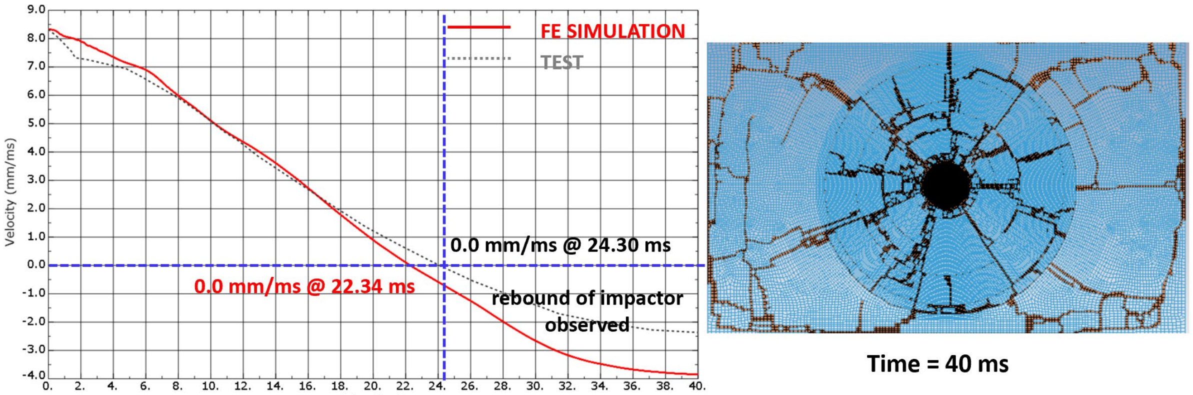
Fig. 11 (a-b): Displacement, velocity, acceleration and crack propagation profile at speed 6.39 m/s with laminated glass configuration (2 mm glass / 0.76 mm interlayer / 2 mm glass).

It was observed in the displacement plot in Figure 11 (a-b) that the difference in predicted vs. measured peak displacement is approx. 2.26% and the difference in time at peak displacement is approx. 1.2%. In the velocity plot, the difference in onset of rebound (time at which impactor starts to move backwards after reaching the peak displacement) is approx. 2.4%. The simulation's acceleration curve showed characteristics similar to the experimental results in spite of the noise (unwanted peak and valley) observed in the simulation, which could be due to hard contact behavior between glass/interlayer and the rigid ball. The predicted crack patterns in the simulation results exhibited expected crack patterns seen in literature. These start with radial cracks originating at the point of impact with further radial cracks distributed equally from the center.

Test#2 – glass-interlayer-glass configuration (2 mm glass / 0.76 mm interlayer / 2 mm glass), impact velocity 8.33 m/s:



(a)

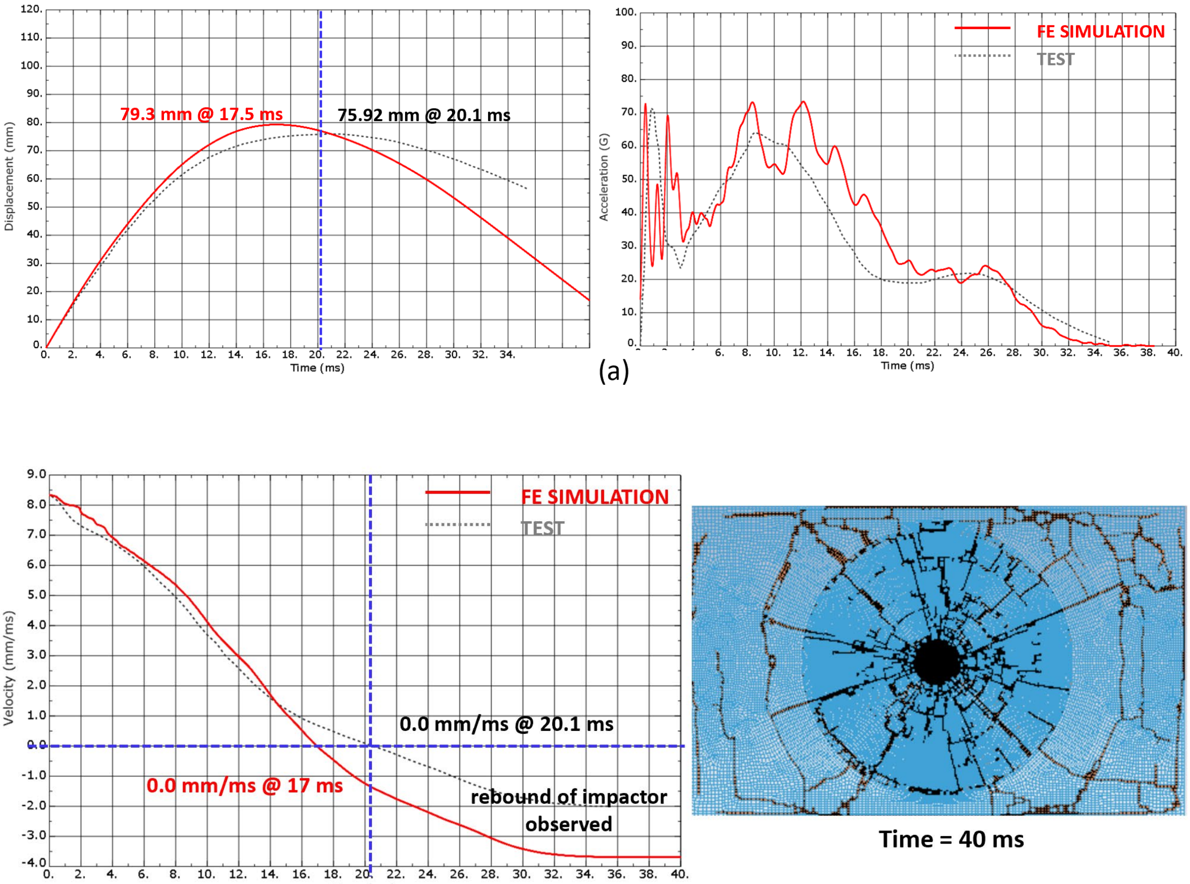


(b)

Fig. 12 (a-b): Displacement, velocity, acceleration and crack propagation profile at speed 8.33 m/s with laminated glass configuration (2 mm glass / 0.76 mm interlayer / 2 mm glass).

It was observed in the displacement plot in Figure 12 (a-b) that that the difference in predicted vs. measured peak displacement is approx. 2.21 % and the difference in time at peak displacement is approx. 8.20%. In the velocity plot, the difference in onset of rebound (time at which impactor starts to move backwards after reaching the peak displacement) is approx. 8.0 %. The simulation's acceleration curve showed characteristics similar to experiment in spite of noise (unwanted peak and valley) observed in simulation. The predicted crack patterns in the simulation results exhibited expected crack patterns seen in literature.

Test #3 – glass-interlayer-glass configuration (2 mm glass / 2.28 mm interlayer / 2 mm glass), impact velocity 8.33 m/s:



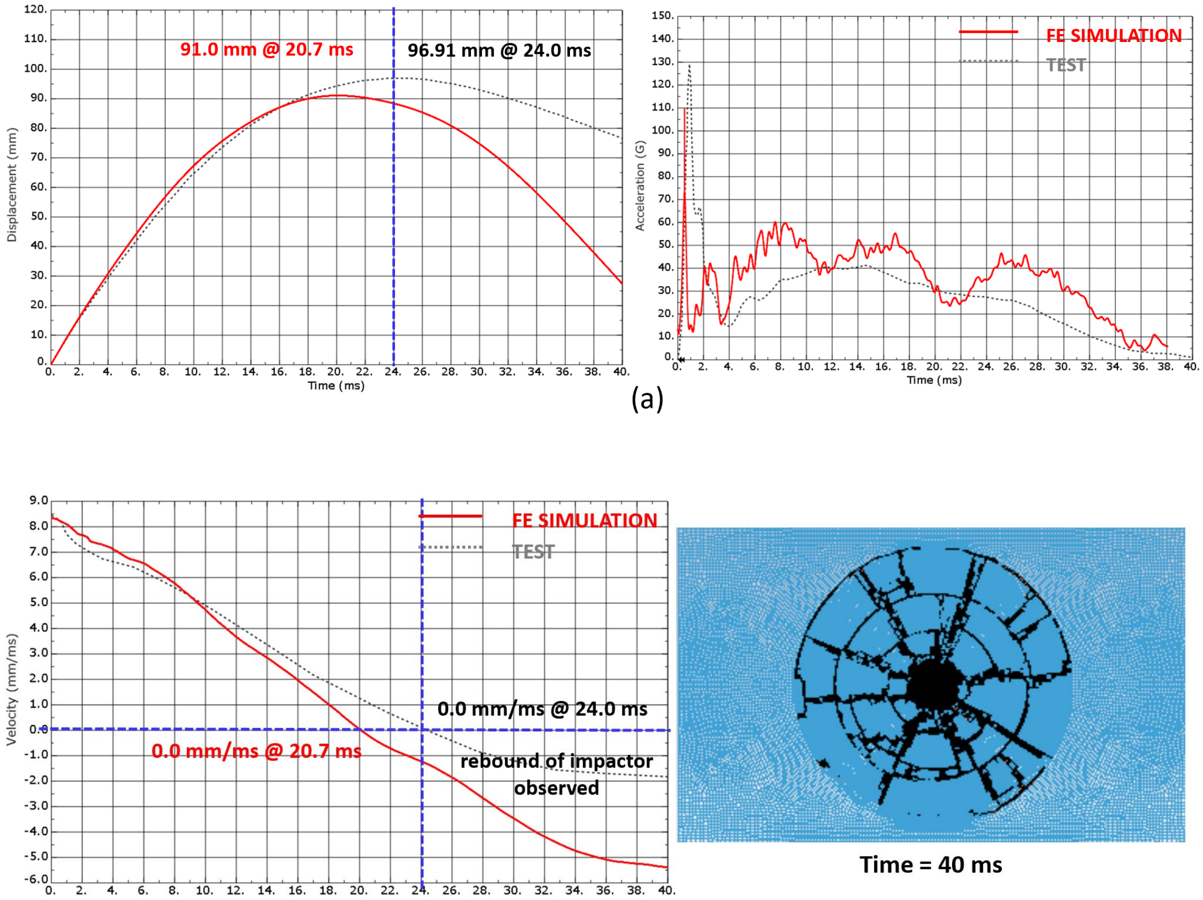
(a)

(b)

Fig. 13 (a-b): Displacement, velocity, acceleration and crack propagation profile at speed 8.33 m/s with laminated glass configuration (2 mm glass / 2.28 mm interlayer / 2 mm glass).

It was observed in the displacement plot in Figure 13 (a-b) that the difference in predicted vs. measured peak displacement is approx. 4.45 % and the difference in time at peak displacement is approx. 12.90%. In the velocity plot, the difference in onset of rebound (time at which impactor starts to move backwards after reaching the peak displacement) is approx. 15%. The simulation's acceleration curve showed characteristics similar to experiment in spite of noise (unwanted peak and valley) observed in simulation. The predicted crack patterns in the simulation results exhibited expected crack patterns in literature.

Test#4 – glass-interlayer-glass configuration (2 mm glass / 0.76 mm interlayer / 4 mm glass), impact velocity 8.33 m/s:



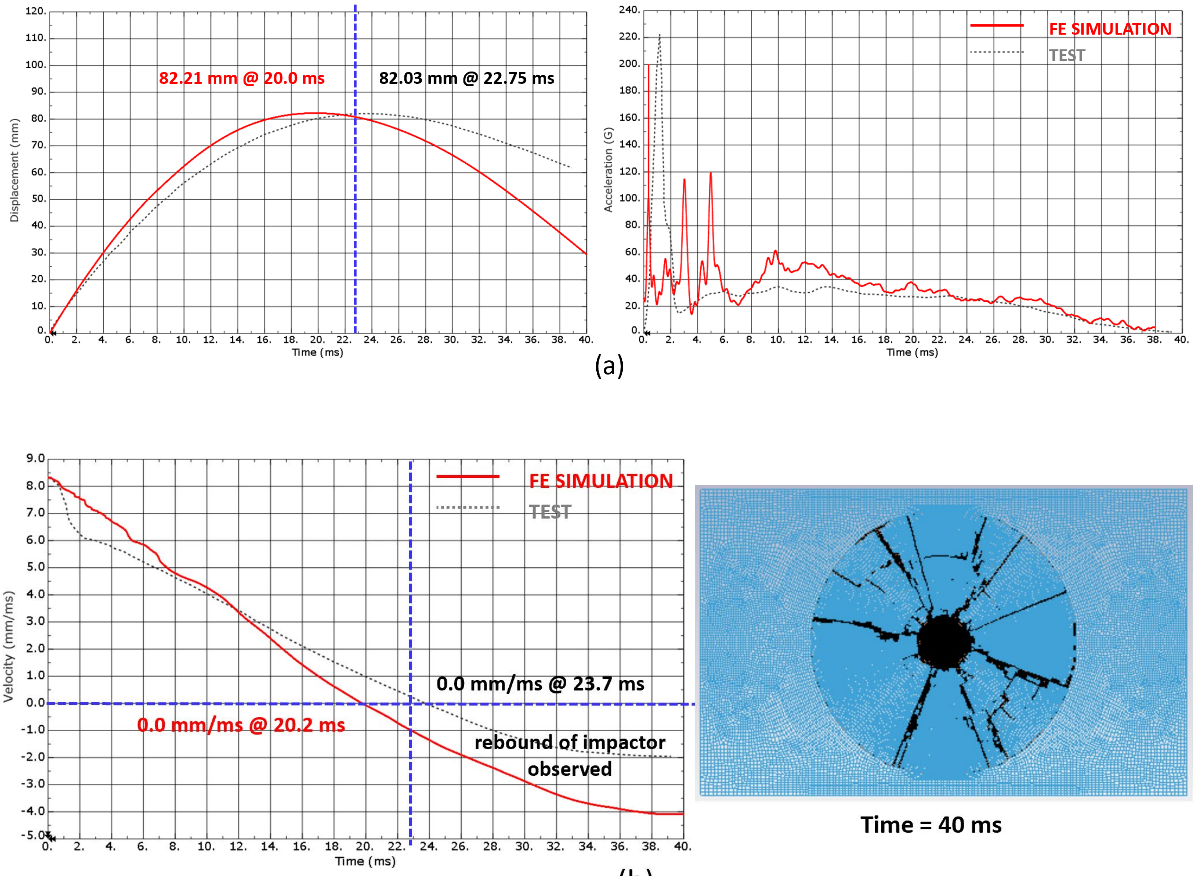
(a)

(b)

Fig. 14 (a-b): Displacement, velocity, acceleration and crack propagation profile at speed 8.33 m/s with laminated glass configuration (2 mm glass / 0.76 mm interlayer / 4 mm glass).

It was observed in the displacement plot in Figure 14 (a-b) that the difference in predicted vs. measured peak displacement is approx. 6.10 % and the difference in time at peak displacement is approx. 13.90 %. In the velocity plot, the difference in onset of rebound (time at which impactor starts to move backwards after reaching the peak displacement) is approx. 13.75%. Then simulation’s acceleration curve showed characteristics similar to experiment in spite of noise observed in simulation. The predicted crack patterns in the simulation results exhibited expected crack patterns seen in literature.

Test#5 – glass-interlayer-glass configuration (4 mm glass / 0.76 mm interlayer / 4 mm glass), impact velocity 8.33 m/s:



(a)

(b)

Fig. 15 (a-b): Displacement, velocity, acceleration and crack propagation profile at speed 8.33 m/s with laminated glass configuration (4 mm glass / 0.76 mm interlayer / 4 mm glass).

It was observed in the displacement plot in Figure 15 (a-b) that the difference in predicted vs. measured peak displacement is approx. 0.2 % and the difference in time at peak displacement is approx. 12.08%. In the velocity plot, the difference in onset of rebound (time at which impactor starts to move backwards after reaching the peak displacement) is approx. 14.76%. Then simulation's acceleration curve showed characteristics similar to experiment in spite of noise observed in simulation. The predicted crack patterns in the simulation results exhibited expected crack patterns seen in literature.

4.4. Parametric Study to Understand the Behavior of Interlayer

Parametric studies have been performed to understand the behavior of the interlayer under different conditions i.e., effect of FE mesh technique, effect of impact speed, effect of interlayer thickness, effect of glass thickness (with constant interlayer thickness), and effect of soft/stiff interlayer material. Table 2 provides the details of the parametric study.

Table 2: Details of parametric study.

	Parameters	Description
1	Effect of FE mesh technique on crack pattern	Circular and Rectangular mesh pattern, Impact velocity 6.39 m/s, Glass configuration 2 mm/0.76 mm/2.0 mm
2	Effect of ball impact speed	Comparison between Impact velocity 6.39 m/s and 8.33 m/s Glass configuration 2 mm/0.76 mm/2.0 mm
3	Effect of interlayer thickness	Comparison between interlayer thickness 0.76 mm and 2.28 mm, Impact velocity 8.33 m/s, Glass configuration 2 mm/0.76 & 2.28 mm/2.0 mm
4	Effect of glass thickness (Symmetric/Asymmertic upper and lower glass thickness)	Comparison among Glass configuration 2 mm / 0.76 mm / 2 mm, 4 mm / 0.76 mm / 4 mm & 2 mm / 0.76 mm / 4 mm, Impact velocity 8.33 m/s
5	Effect of soft and stiff interlayer material	Interlayer material properties scaled by 3 times to get stiffer behavior and compared with original (soft) material properties, Impact velocity 6.39 m/s, Glass configuration 2 mm/0.76 mm/2.0 mm

Effect of mesh technique on crack pattern:

An important goal in FE simulations is to have mesh-independent results. This is often achieved by increasing overall mesh density. However, mesh patterns and size gradients can also have an impact on simulation results. In this study, the impact of a fully rectangular mesh pattern vs. a circular mesh pattern was investigated. In both cases, the simulations predicted laminated safety glass crack patterns similar to those seen in experiments; however, there were distinct differences in the crack pattern and peak displacement depending on meshing method used as shown in Figure 16. The crack patterns using the rectangular mesh had more non-radial components (Timmel et al. 2007). It was observed in the displacement plot that the difference in the predicted peak displacement for the two meshing methods is approx. 7 mm, which is significant. However, the difference in onset of impactor rebound seen in the velocity plot showed no significant time difference.

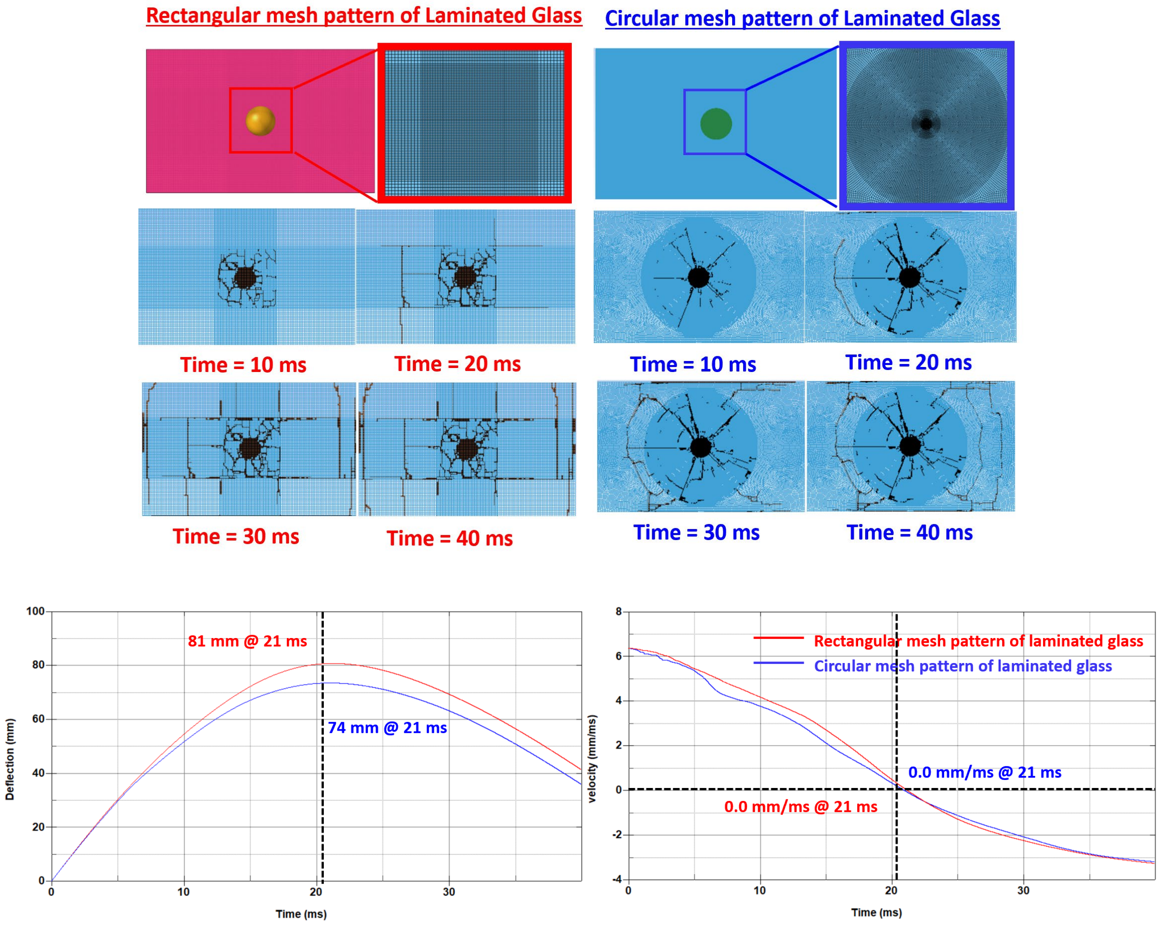


Fig. 16: Effect of mesh technique on crack pattern at velocity 6.39 m/s.

Effect of ball impact speed:

The impactor drop speed (low = 6.39 vs. high = 8.33 m/s) with the same interlayer material, has significant influence on the simulation results. This is evident from differences in crack pattern, displacement curves, and velocity curve seen in Figure 17.

It was observed that peak displacement was significantly higher and was reached at an earlier time for the simulation at high impactor speed as compared to low speed. The velocity plot also shows a corresponding difference in rebound onset time. The predicted crack patterns of the laminated glass indicate more damage with higher impact speed due to higher energy. Higher impact speed showed higher deformation and, more damage as compared to lower speeds, which is in-line what is given in literature (Dural 2020).

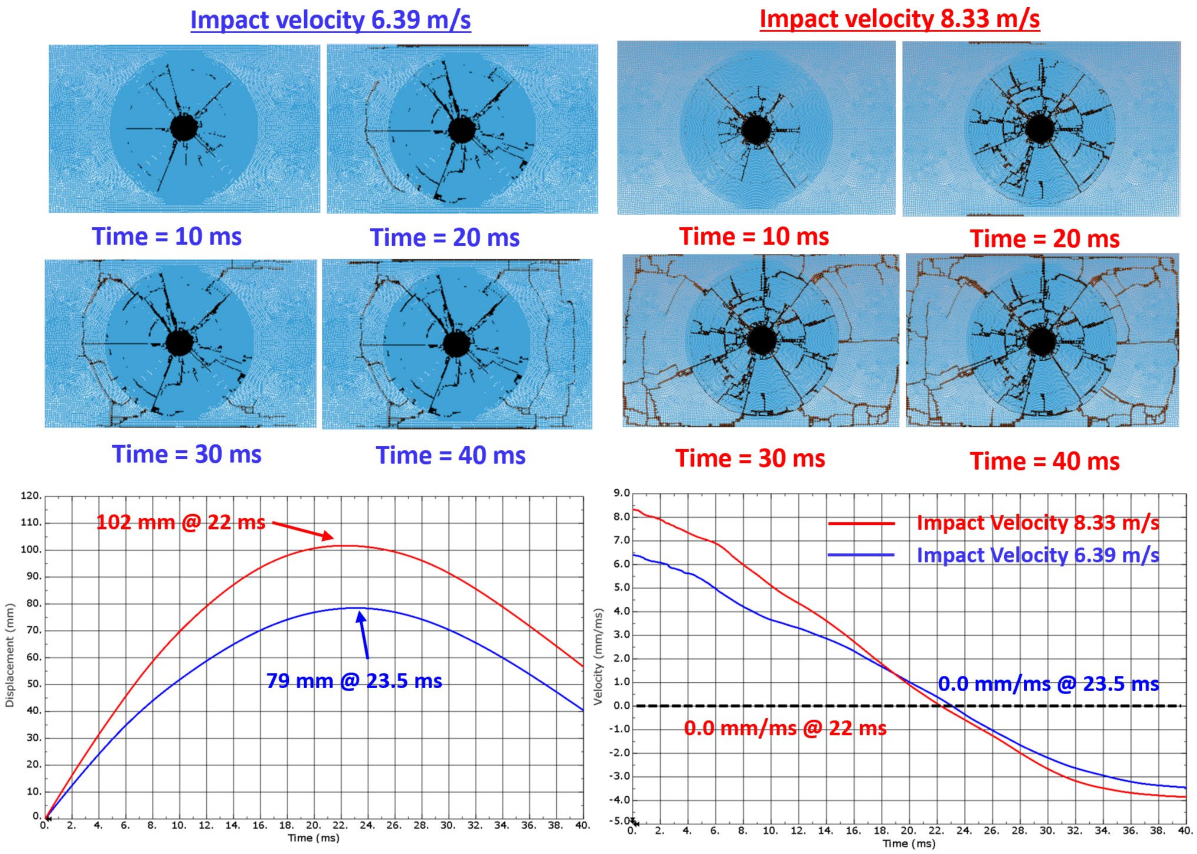


Fig. 17: Effect of ball impact velocity on displacement, velocity and crack propagation.

Effect of interlayer thickness:

The interlayer thickness (low = 0.76 mm and high = 2.28 mm), with the same interlayer material, has a significant influence in the drop test simulation results. This is evident from difference in crack pattern, displacement curves, and velocity curves seen in Figure 18.

It was observed that peak displacement was significantly higher and was reach at a later time for the simulation at low interlayer thickness as compared to high thickness. This indicated that high interlayer thickness has more stiffening effect than low interlayer thickness. The velocity plot also shows a corresponding difference in rebound onset time. The predicted crack patterns of the laminated glass indicate less damage with a thicker interlayer due to the increase in stiffening behavior. High interlayer thickness showed less deformation and more damage as compared to low interlayer thickness, which is in-line with what is given in literature (Huang et al. 2021).

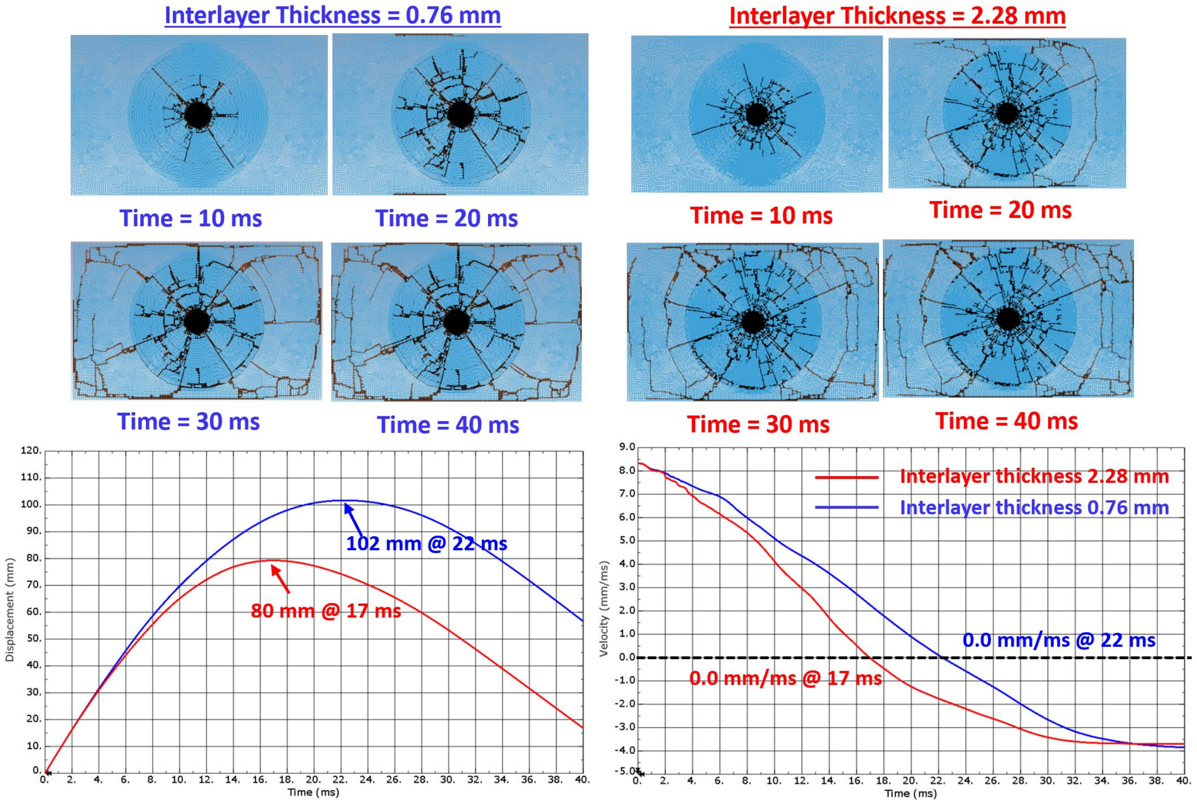


Fig. 18: Effect of interlayer thickness on displacement, velocity and crack propagation.

Effect of glass thickness:

Comparison of 2 mm/0.76 mm/2 mm and 4 mm/0.76 mm/4 mm glass configuration:

Glass thickness (low = 2 mm and high = 4 mm), with the same interlayer thickness and material, has a significant influence on the drop test simulation results. This is evident from difference in crack pattern, displacement curves, and velocity curves seen in Figure 19.

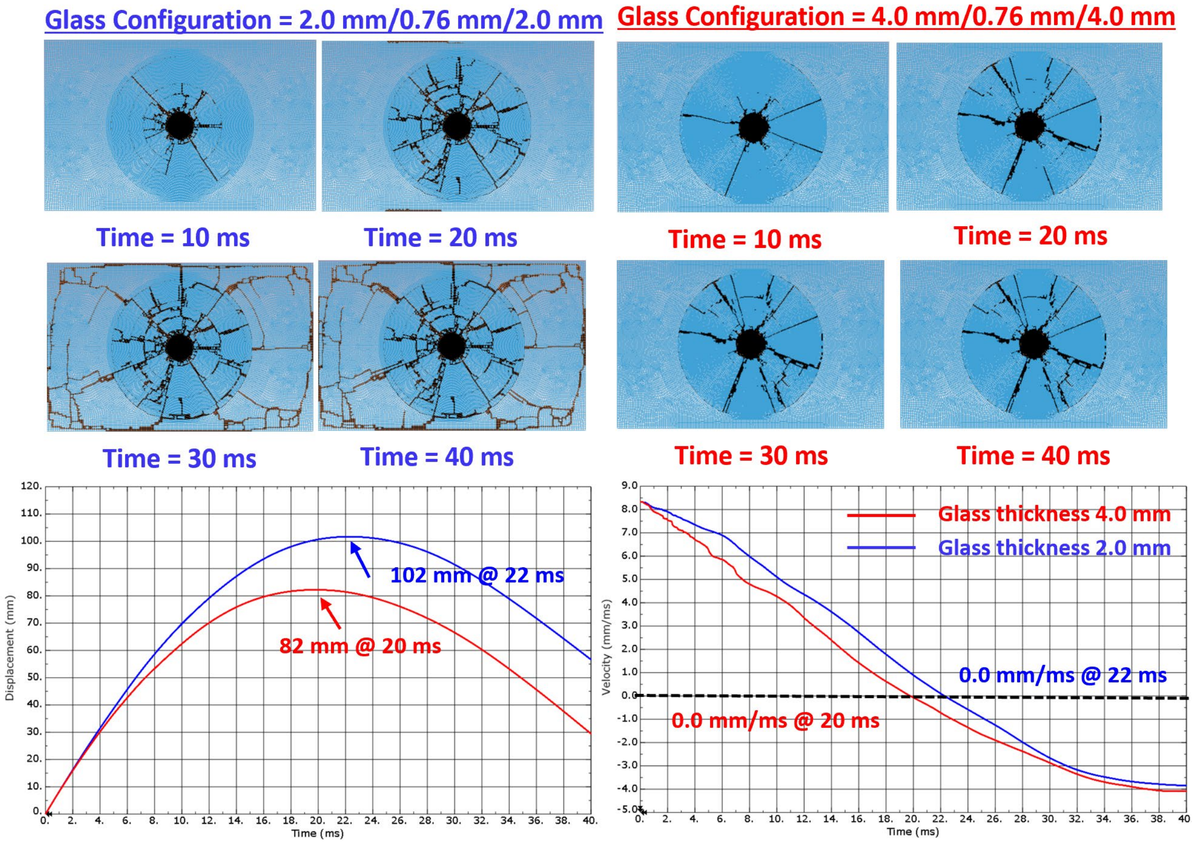


Fig. 19: Effect of glass thickness on displacement, velocity and crack propagation.

It was observed that the peak displacement was significantly higher and was reached at a later time for the simulation using low glass thickness as compared to high glass thickness. This indicated that high glass thickness has more resistance to impact than lower glass thickness. The velocity plot also shows a corresponding difference in rebound onset time. The predicted crack patterns of the laminated glass indicate less damage with thicker glass layers. High glass thickness showed less deformation and, significantly less damage as compared to low glass thickness, which is in-line with given in literature.

Comparison of 2 mm/0.76 mm/2 mm (symmetrical layer structure) and 2 mm/0.76 mm/4 mm (asymmetrical layer structure) glass configuration:

A variation of the glass thickness parameter is to have a thicker glass layer only on one side, in this case on the side that is not directly impacted by the ball. The resulting crack patterns, displacement curve, and velocity curve seen in Figure 20 (in comparison to the case of two thin glass layers) tend to lie between the cases with two thin glass layers and two thick glass layers as shown in Figure 19.

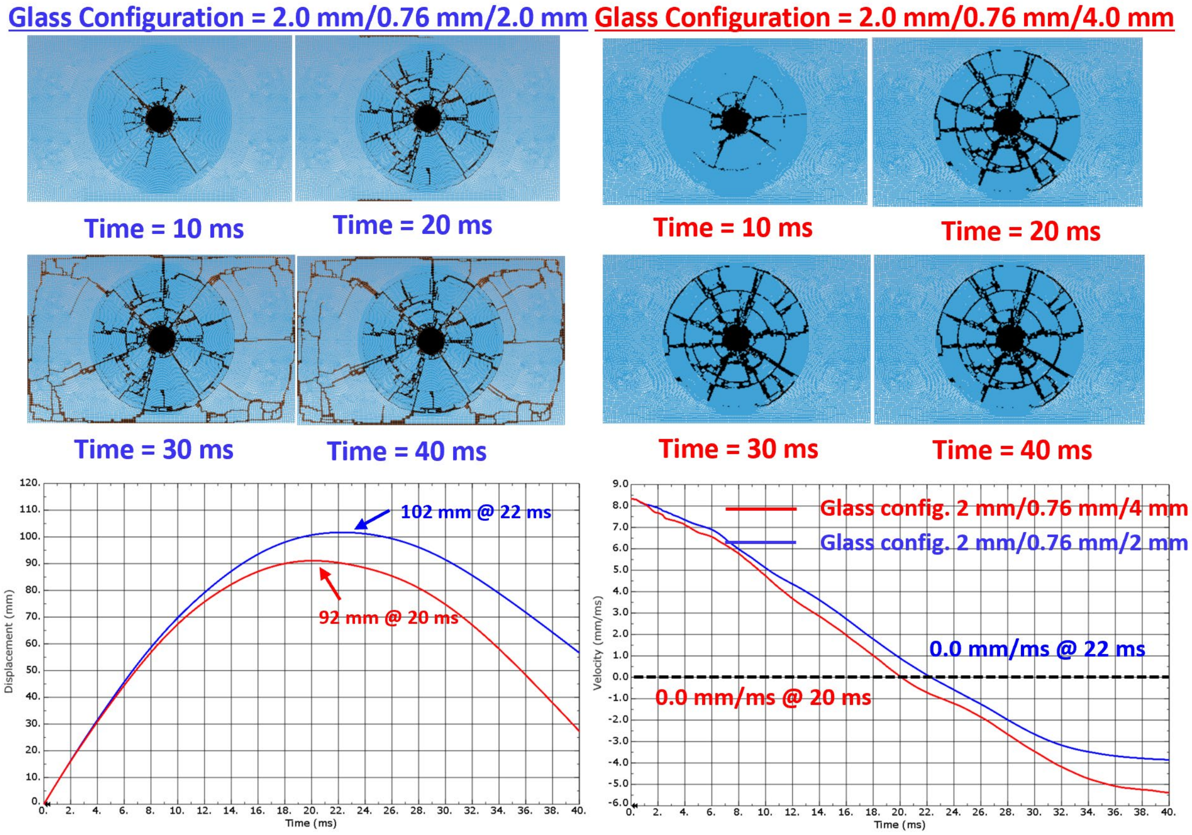


Fig. 20: Effect of variable glass thickness on displacement, velocity and crack propagation.

The peak displacement value increase and the time to reach peak displacement decrease as you move from the configuration with two thin glass layers (2 mm/0.76 mm/2 mm) to the configuration with one thin and one thick glass layer (2 mm/0.76 mm/4 mm) and finally to the case with two thick glass layers (4 mm/0.76 mm/4 mm). This indicated that, in general, thicker glass layers (with the same interlayer thickness) improve the resistance to impact. The velocity plots show a corresponding decrease in rebound onset time with an increase in the number of thick glass layers. The predicted crack patterns of the laminated glass indicate less damage with an increase in the number of thick glass layers.

Effect of soft and stiff interlayer material:

Interlayer material properties (soft and stiff behavior in uniaxial tensile test data) have significant influence on the drop test simulation results. This is evident from differences in crack pattern, displacement curves, and velocity curves seen in Figure 21.

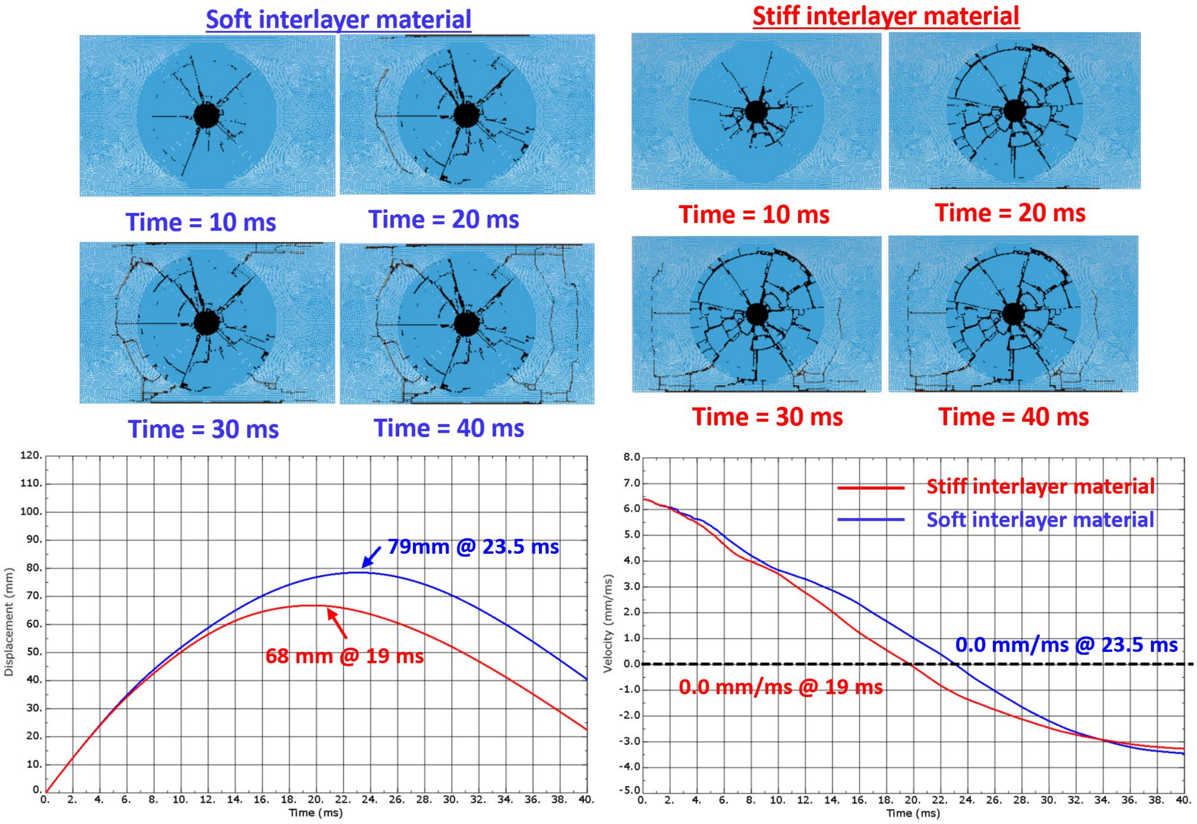


Fig. 21: Effect of Soft/Stiff interlayer material on displacement, velocity and crack propagation.

It was observed that peak displacement was significantly higher and was reached at later time for simulations with soft interlayer material properties as compared to stiff interlayer material properties. This indicated that stiff interlayer materials have more resistance to impact than soft interlayer materials. The velocity plot also shows a corresponding difference in rebound onset time. The predicted crack patterns of the laminated glass indicate less damage with soft interlayer materials. Stiff interlayer material showed less deformation and significant higher damage as compared to the soft interlayer material, which is in-line with what is given in literature (Xiaowen et al. 2019; Kamarudin et al. 2019).

5. Conclusions

Glass laminate films (the adhered interlayer between sheets of glass) are an important component of many glass applications. It is clear from the literature review that a lot of research work is done in the field of laminated safety glass that includes analytical models, experimental studies, and numerical simulations. Extensive research has been conducted on various kind of loadings (static, dynamic or blast loading) of laminated glass.

Finite Element models are capable of predict qualitatively and, quantitively, realistic fracture behavior of laminated glass leadings to reasonable agreements with experimental findings from literature. The numerical model results are helpful in understanding interlayer characteristic (thin, thick, soft and stiff) and the ability to capture the fracture process, i.e., initiation and propagation of cracks with the use of advanced techniques such as element deletion and cohesive modeling. Furthermore, the numerical model can be used to identify the composite efficiency of laminated glass in a simple four-point bending, impact and blast tests.

In this study, the response of laminated safety glass in four-point bending loading and impact loading conditions was studied by using the Finite Element Method. Commercial finite element software packages ABAQUS standard and LS-DYNA explicit was used in the study.

Static four-point bending simulations are carried out with different glass and interlayer thicknesses. From simulation outcome, it is observed that interlayer thickness has significant influence on bending behavior of laminated glass. The simulations were able to qualitatively capture the force vs. displacement curve characteristics seen in the experimental data, with close quantitative agreement (with in 10-15%) on the maximum value to force and displacement.

Also in this study, dynamic impact simulations are carried out with different glass & interlayer thicknesses and different velocities. In addition, parametric studies were conducted to evaluate the effect of the meshing method, impactor speed, interlayer thickness, glass layer thickness, and the interlayer material properties (soft/stiff).

The important points observed from the dynamic loading (impact) studies include:-

- Mesh technique has significant influence on crack pattern (radial vs non-radial).
- An increased impactor drop height (high velocity) creates a denser fracture pattern, and increases the risk of impactor penetration. Displacement and stress of laminated glass unit significantly increase with increasing impact velocity.
- Doubling the interlayer thickness reduces the risk of object penetration. Additionally, it does not compromise the dynamic structural integrity of the laminated glass.
- Doubling the glass thickness substantially enhances the structural integrity and the impact resistance of the specimen.
- Thin laminate glass with thin interlayer has considerable maximum transverse central displacement and insignificant first peak contact force.
- An increased interlayer stiffness enhances the structural integrity of the specimen. It was shown that a stiffer interlayer material leads to greater contact force and lower transverse central displacement of laminated glass. The stiffest polymer interlayer provided the highest elastic bending strength to the laminated glass, resulting in the best load carrying capacity after the fracturing of the glass layers at room and high temperatures.
- Laminated glass provides its safety through the maintenance of the bond between the glass and the interlayer, and through the deformation of the interlayer. The amount of deformation is related to the stretching of the interlayer, which is related to the amount of adhesion between the glass and the interlayer.
- In general, the current numerical model is capable of predicting accurately the dynamic response, i.e., displacement, velocity and acceleration, of laminated glass with different thicknesses under various impact velocities. The simulations were able to qualitatively capture the displacement curve characteristics seen in the experimental data, with close quantitative agreement (within 10-15%) on the maximum value of displacement. Similarly, the simulations were able to capture the velocity vs. time curve characteristics seen in the experimental data up to the point of rebound. Differences seen in the rebound phase could be due to differences in viscoelastic (damping) behavior of interlayer

between actual and simulation material behavior. The simulations were also able to qualitatively capture the acceleration curve characteristics seen in the experimental data, with close quantitative agreement (within 10-15%) on the maximum value of acceleration. The numerical results are helpful in the design of laminated glass with desired damage characteristics.

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