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Finite element analysis of laminated glass

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Abstract

In the road and rail industries, annealed float glass is combined with a thin polymeric layer to form a 3-ply glass/PVB/glass structure known as laminated glass. Amongst other characteristics, the PVB acts to retain fractured glass fragments, thus minimising injury from flying glass shards. Previous attempts at predicting the behaviour of laminated glass during impact have proven difficult due to complex stress fields caused by the large differences in moduli. The following research made an attempt at modelling laminated glass using the Laminated Glass model of LS-DYNA (MAT_32). Experimental results, used for model validation, displayed a large amount of scatter that may have been due to differences in manufacturing conditions. Numerical prediction results showed the model to be highly sensitive to mesh refinement. The resultant data showed poor correlation with experimental results predicting a much softer response.

Keywords: Laminated Glass; Finite Element; Impact; LS-DYNA; MAT_32; Polyvinyl Butyral (PVB).

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Introduction

1.1 Background

Originating over six thousand years ago, glass is considered to be one of the world's oldest man-made composite materials. Glass is processed from a mixture of silica (sand), soda ash, limestone and various other elements that are melted together at around 1600°C. During processing, it is possible to achieve different strength and fracture control properties by using a variety of chemical or heat treatment methods. Untreated glass will shatter into large and sharp pieces once its elastic limit is exceeded.

Safety glass is defined by the British Standards Institution as “a glass which, if fractured, is less likely to cause severe cuts or serious physical injury than ordinary glass” (BS 857, 1967). This criterion can be easily met by modifying the processing technique. The glass can be heat-strengthened, annealed or tempered so that when a critical load is reached the glass will shatter into small and blunt pieces. In the automotive sector, soda-lime-silica float glass (in the annealed state) is combined with a thin polymeric layer (typically 0.76 mm) to form a 3-ply glass/polymer/glass structure known as laminated safety glass. The industry standard polymer, used for road transport, is polyvinyl butyral (PVB) as it provides excellent optical and adhesive properties.

Laminated glass offers several performance benefits over contemporary glass; allowing for a reduction in its thickness, thus saving weight. The possibility of skull fracture during a collision can be diminished by reducing the thickness of the glass layers (Flocker and Dharani, 1997a). The PVB interlayer behaves as a highly viscous adhesive and acts to retain fractured glass fragments, thus minimising injury from flying glass shards in a crash situation. Secondly, PVB also helps to distribute the energy generated on impact. For small deformations, where the laminated glass is subjected to low strains, the PVB acts as a rubbery elastic. However, at high strains with large deformation (i.e. a crash situation) the PVB acts as a glass-like linear elastic material (Du Bois,

Kolling and Fassnacht, 2003). During severe dynamic loading, such as impact, the PVB is used to cushion the impact to an occupant and prevent occupant ejection by absorbing contact energy as the PVB is stretched. The PVB also works as an adhesive to bind the two plies of glass in order to keep shattered glass in place when broken.

In the automotive industry, the use of laminated glass windscreens was first implemented by the Ford motor company in 1926 (McKay, 2008). More recently, laminated glass has been used in the coach/bus, rail, and marine industries. The utilization of laminated glass in the automotive sector is rapidly extending, where it is used for sunroofs, side and rear windows in new automobiles (Zhao et al, 2006). It is believed that laminated glass helps protect occupants from injury during impact and has proven to help limit the possibility of occupant ejection in the event of vehicle rollover. Huntsberger (1981) found that the performance of windscreens (during impact) can be optimised by controlling the amount of delamination or bonding strength of the glass and interlayer. In the architectural sector, laminated glass plays an important role in resisting debris in severe weather conditions as well as providing excellent safety and security to occupants.

In order to fully understand the failure mechanisms of glass, a thorough review of the literature is required. Traditionally, solid-state research has focused upon crystalline materials. However, in recent years, solid-state research has been conducted in the area of solids that do not have a crystal structure; materials known as amorphous or non-crystalline solids. Amorphous solids have no long range order and are most commonly referred to as glasses (Zallen, 1983). Glass exists in a solid yet transparent state; it has motionless molecules that are randomly configured bearing resemblance to both a solid state and liquid state material (Glass on Web, 2002). When cooled from a liquid, glass solidifies continuously to an amorphous solid (Zallen, 1983). If the viscosity rises high enough, as the glass cools, an amorphous solid will be produced. Glasses are solids with extremely high viscosities. Research conducted by Lloyd (2008) has shown, using colloids, that the glass particles attempt to crystallise but fail due to the formation of icosahedra like structures. In the past, glass has been

referred to as a super-cooled liquid, in reference to its microstructure, which remains as a liquid below its melting point due to no nucleation sites to initiate crystallisation (Gibbs, 1996). Below the glass transition temperature, T_g , the glass remains in its vitreous or amorphous but solid state, above the melting temperature, T_m , glass is in the liquid state. However, between T_g and T_m glass is sometimes referred to as a super-cooled liquid as noted above. However, T_g , is dependent on the cooling rate (Gibbs, 1996).

Historically, it was thought that glass was susceptible to creep. This can be illustrated with old church windows, where the thickness is noticeably greater at the bottom. However, this common misconception is untrue. In fact, the difference in thickness can be attributed to the Crown manufacturing technique, where molten glass is rolled, blown, expanded, flattened and finally spun into a disc before being cut into panes (Gibbs, 1996). During the spinning process, the panes become thicker towards to outer edge of the disc. The window pane is then installed with the thicker and heavier edge at the bottom. An example that shows glass does not flow is in 150 year old telescopes that still have excellent optical qualities (Gibbs, 1996). The modern 'floating' manufacturing technique is used by many glass manufacturers as it produces high quality, flat glass sheets. During this process, molten glass is floated in molten tin; the glass is then slowly cooled, annealed and then heat treated (Callister, 2007).

During the cooling of ceramic materials thermal stresses may be introduced due to the differences in cooling rate and thermal contraction between the surface and inner regions (Callister, 2007). These thermal stresses weaken the material and, in extreme cases, can lead to fracture. Annealing of ceramics relieve stresses whereas thermal tempering introduces residual stresses (compressive) in order to increase material strength.

Glass will almost always fracture before there is any plastic deformation at room temperature; a characteristic shared by the majority of ceramics. Once a crack has initiated, it will continue to propagate until a critical velocity is reached where branching or bifurcating occurs. Glass fractures with no prescribed

manner or direction and is likely to be affected by the microstructure of the glass, the stresses that are present and elastic waves caused by impact (Callister, 2007). The fracture characteristics of laminated glass are largely determined by its variable strength due to randomly introduced Griffith flaws. At a critical load, cracks open and extend at the location of the maximum tensile stress (Zhao et al, 2006). Flocker and Dharani (1997b) analysed these cracks and found that, during the impact of a spherical projectile on a brittle material, glass produced Hertzian cone cracks (see section 2.3.4).

Complex stress fields, due to a large difference in moduli between the glass and PVB ($E_{\text{glass}}=10^{10}$ and $E_{\text{PVB}}=10^6$), make the prediction of material behaviour complicated (Bennison, Jagota and Smith, 1999). Many authors have found modelling laminated glass a challenging task. Often, assumptions are made that limit the validity and accuracy of the model by over simplifying fracture characteristics and poorly characterising materials. Previous work has mainly focused on the mechanical properties of the analysis using real applications. Thus, the created models could not be used for more universal analyses (Iwasaki et al, 2007). This research will take into consideration many of these assumptions and will attempt to improve upon previous research.

12 Aims and Objectives

The aim of this project is to use Finite Element Analysis to model laminated glass subjected to impact. The numerical simulation will be processed using the dynamic, impact specialist, nonlinear three-dimensional Finite Element code LS-DYNA (Livermore Software Technology Corporation, 1997). The difference in modulus between the glass and PVB, the fracture characteristics of glass and the difficult-to-characterise PVB interlayer make this a challenging task. This model is intended for generic use across a wide range of applications.

In order to meet the aims of the project, the following objectives must be realised;

- I Develop and implement a method for experimental testing

- II. Investigate the material properties and characteristics of monolithic and laminated glass as well as the PVB interlayer.
- III. Investigate the behaviour of laminated glass when subject to high dynamic loading, such as impact.
- IV. Develop and implement a Finite Element (FE) model (using the pre-processors Hyperworks and Primer)
- V. Investigate a range of numerical analyses (using LS-DYNA) in order to explore the material behaviour and fracture and failure characteristics of laminated glass.
- VI. Validate the computer simulation using experimental test results and statistical theories.
- VII. Develop an FE model capable of replicating the elastic and failure responses of laminated glass subjected to dynamic loading over a range of impact velocities.

This research will attempt to develop a model that characterises the fracture and failure of laminated glass specifically for impact vulnerable applications. The main concern of the research is with laminated safety glass used in land transport.

13. Project Plan and Report Outline

This project has been sub-divided into categories dependent on their role within the research. A Gantt chart (see Appendix A) has been devised in order to maintain good time management as well as to help keep track of progression throughout the project. It can be seen from the Gantt chart that project milestones have been added.

The project will benefit from a thorough literature review of past and present research of FE analyses of laminated glass. The project will further benefit from personal communication with the industrial contributor and the staff of Cranfield Impact Centre that have knowledge and experience in this area. This can be found in Chapter 2 which also gives a basic introduction into the theoretical

background of the manufacturing processes of glass and material behaviour when subjected to impact. This chapter is largely influenced by the aims and objectives that can be found in section 1.2 of Chapter 1. Characterisation of material is an important aspect of numerical simulation and therefore is worthy of in-depth analysis that can be found in Chapter 3. The methodology of numerical simulation and experimental testing can be found in Chapters 4 and 5 respectively. This is where techniques and procedures are described in great detail. The results section, Chapter 6, gives an overview of the results of this research. Raw data and high speed video is accessible on compact disc and forms part of Appendix B. Chapter 7 reports a factual argument on the findings of the research. This chapter will give an in-depth analysis of the results and will closely relate to Chapter 6 making reference to the data. Finally, in Chapter 8, the research is concluded with a list of concise conclusions on the value of this research. This chapter also includes a list of the future recommendations and developments of the research.

Theoretical Background and Literature Review

2.1 Brittle Ceramics and Glass

Generally, glass materials are extremely hard with low density and have poor resistance to impact (Buchar *et al*, 2001). Ordinary glass is an extremely brittle isotropic ceramic that is susceptible to shatter even when subjected to a small amount of shock loading. The strength of glass is largely determined during the processing stage where the residual stresses in the glass can be controlled. At room temperature, glass shows very little plastic strain (no yield) before failure; i.e. the stress-strains curve of glass shows almost perfect linearity. It is for this reason that the plastic strains in glass are often considered to be negligible meaning glass can be treated as a perfectly elastic material with brittle failure.

2.2 Safety Glass

Safety glass has been defined as a glass that, if fractured, is less likely to cause injury than ordinary glass (BS 857, 1967). The most common types of safety glass are toughened glass (also known as tempered), laminated glass, heat-treated glass (also known as heat-strengthened), wired glass and plastics glazing glass. The literature sometimes refers to annealed or toughened glass as being heat-treated which, in terms of definition, is technically inaccurate. Although annealed and toughened glass is heat treated, the annealing and toughening processes refer to the cooling technique. Therefore, in order to clearly define the three separate processes heat-treated glass will be referred to as 'heat-strengthened' glass.

Toughened glass is produced when annealed glass is thermally or chemically tempered. Chemical tempering of glass is used to process glass that is less than 1.5 mm thick but is undesirable due to the hazardous waste produced. Thermal tempering of glass allows for good controllability and is a cleaner yet more expensive manufacturing technique. Thermal tempering is an additional process whereby glass is heated to around 600°C (above its annealing point) then rapidly cooled by large jets of air or quenched in water (Kolling, Haufe and Du Bois, 2005). As the outside of the glass cools quicker than the inside,

residual stresses are introduced that strengthen the glass. These residual stresses are caused by the differences in post solidification cooling rates. Once the outer surfaces of the glass have cooled, introducing compressive stresses, the inside of the glass is subjected to tensile stress. The residual stress distribution is illustrated in Figure 1. Toughened glass can be up to four times stronger than annealed glass and will shatter into small blunt pieces once its elastic limit is exceeded (Glass on Web, 2007). The tensile strength of toughened glass is largely dependent on strain rate. At a low strain rate, the glass is flexible whereas at high strain rates, such as impact, the glass will shatter into small and blunt pieces. It is for this reason that toughened glass is not used in the automotive industry, as a small stone travelling at a high velocity could shatter the windscreen causing injury to the vehicles occupants. However, in some vehicles toughened glass is used for side and rear windows, usually in place of laminated glass as the toughened glass option is more cost effective.

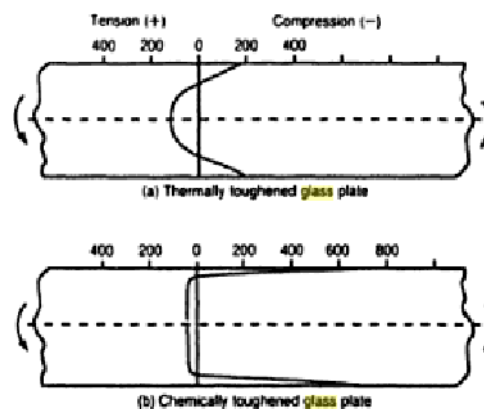


Figure 1. Residual stress distribution of thermally tempered (toughened) glass, stresses measured in MN m^{-2} . (Taken from Smallman and Bishop, 1999).

Applying a large dynamic load on a small area of toughened glass would cause it to fracture into very small pieces. This can be seen in Figure 2.

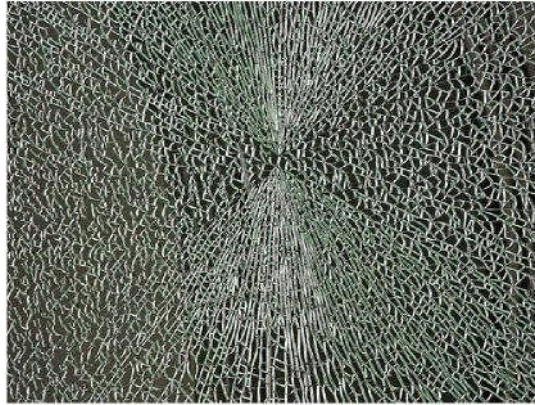


Figure 2. Thermally tempered glass fractured into small blunt pieces. (Taken from First Class AutoGlass, 2008).

The performance characteristics of heat-strengthened glass lie between that of toughened and annealed glass. Heat-strengthened glass is stronger than annealed glass but weaker than toughened glass. Once its elastic limit is reached heat-strengthened glass fractures into moderately sized sharp pieces (in comparison with annealed and toughened glass). Annealed glass is produced when molten glass is heated above its 'annealing point' then slowly cooled to relieve the internal residual stresses. The annealing point (annealing temperature) of annealed glass is the temperature at which its viscosity reaches 10^{12} Pa s (Le Bourhis, 2007). The temperature during cooling (the cooling rate) is controlled in an oven called a Lehr (Hogg, 2009).

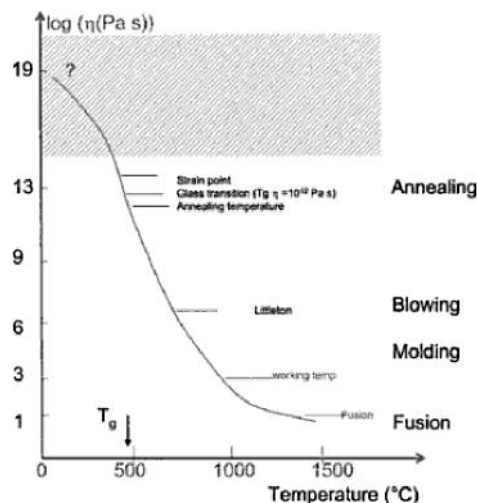


Figure 3. Viscosity as a function of temperature below and over. (Taken from Le Bourhis, 2007).

Residual stresses relax as the temperature throughout the glass equalises. The glass is cooled at a slow enough rate that there is a negligible temperature difference between the surface and inner region of the glass. The cooling process can take several hours and will be completed once the residual stresses in the glass have been relieved. However, annealed glass cannot be categorised as safety glass due to the large and sharp shards that are produced during fracture.

Annealed glass is sometimes referred to as 'ordinary glass' due to the fact that during the float glass manufacturing process the glass is heated to the annealing point and then cooled at a slow enough rate to relieve residual stresses. The glass is heated so that the temperature is consistent throughout the glass and then slowly cooled to room temperature. The strength of annealed glass is greater than that of untreated glass where residual stresses remain. High quality annealed glass is used for laminated glass windscreens in the automotive industry. The applications of laminated glass will be discussed further in section 2.2.5.

2.2.1 Float Glass

The float process, also known as the Pilkington Process, is a technique developed by Alastair Pilkington in the 1950's (Wurm, 2007). Float glass is produced when liquid glass is poured onto a bath of molten tin at around 1550°C - 1600°C. In order to prevent oxidation during the float process, a positive pressure consisting of nitrogen and hydrogen is applied to the atmosphere. It has been reported that tin impurities can be found in the tin-side of float glass. It has further been reported that there is a difference in mechanical properties between the tin-side and air-side. This will be discussed in depth in section 2.3.6.



Figure 4. Glass liquid melt floating on molten tin. (Taken from Pilkington, 2009).

The thickness of the glass can be controlled using different roller speeds during the drawing process. Pilkington (2009) are able to manufacture float glass in thicknesses between 0.3 mm and 25 mm. The drawing process usually takes place in the Lehr, where the glass is slowly cooled and becomes free from residual stresses. This is where the glass is cooled to 500°C over a quarter mile distance and finally, now just above room temperature, the glass is scored and broken (not cut) then sent for storage/delivery (Hogg, 2009).

The composition of materials used for the liquid melt varies from manufacturer to manufacturer. Independent Glass (2009) uses a melt that comprises of a mixture of materials consisting of around 10-20% cullet/recycled glass. The raw materials consist of around 60-70% silica/sand, 10% sodium oxide/soda ash, 10% calcium oxide/limestone. Although transparent, glass appears to be slightly green due to iron impurities. Overall, the float process can produce good quality, flat panes of glass with uniform thickness and is the most commonly produced commercial glass on the market, constituting 90% of the total production of glass (Glass on Web, 2004).

2.2.2 Laminated Safety Glass

Laminated glass is a composite material constructed from two or more layers of glass with an interlayer or several interlayers that usually increase the safety and performance of the structure. Laminated glass was first invented by Edouard Benedictus in 1910 under the name Triplex (Ballard Bell and Rand,

2006). Even to this day, laminated glass consists of a polymeric interlayer sandwiched between two plies of safety glass and is designed so that fracture should not cause the glass to fully separate from the interlayer. Research conducted by Bennison, Jagota and Smith (1999) found that laminated glass proved to be far superior to monolithic glass of identical thickness. The glass plies can be annealed, heat-strengthened or tempered depending on the application. The fracture and failure characteristics of laminated glass will be discussed further in section 2.3.

Annealed laminated glass is manufactured by first washing the individual panes of glass to remove residue induced during handling. The glass is then dried and taken to a clean room (dust free) where the temperature and humidity are measured and precisely controlled. The polymer interlayer is then accurately positioned and cut to size when placed over what will become the bottom pane of the laminated glass. The second pane of glass is then subsequently cleaned, picked up using vacuum suction pads, and accurately placed on top of the polymer interlayer. The laminated glass is then sent through a heated roller system (Figure 5) that softens the interlayer and removes any air bubbles.



**Figure 5. Heated roller system to soften interlayer and remove air bubbles.
(Independent Glass Co Ltd, 2009).**

The final process used to manufacture laminated glass is where the layers are fused together using high temperature and pressure. This process is conducted

in an autoclave; the production cycles for the glass used in this research can be found below in Table 1 where temperature is measured in Celsius and pressure is measured in Bar.

Table 1. Autoclave cycle for laminated annealed glass with a PVB interlayer. (Gilleeney, 2009).

PVB Annealed Cycle					
TEMPERATURE PROFILE					
	Step 1	Step 2	Step 3	Step 4	Step 5
Final Value (°C)	90	90	140	140	40
Max Gradient (°C)	1.5	0	1.5	0	0.7
Maintenance (minutes)	0	15	0	85	0
PRESSURE PROFILE					
	Step 1	Step 2	Step 3	Step 4	Step 5
Final Value (bar)	4	4	12	12	12
Max Gradient (bar)	0.17	0	3	0	0.5
Start Temperature (°C)	0	0	0	0	50
SV Temperature (°C)	4	4	12	12	0

2.2.3 Laminated Glass Interlayers

The most recognised industry standard polymer interlayer is PVB however, polymers such as polyurethane (PU), polyvinyl chloride (PVC) and ethylene vinyl acetate (EVA) have also been used (Azapagic, Emsley and Hamerton, 2003). A common polymeric interlayer that is used in the architectural is DuPonts Ionoplast SentryGlas which claims to be 100 times stiffer and 5 times stronger than traditional interlayers (DuPont, 2009). PVB is the industry standard interlayer used in the automotive industry and is sometimes classified as a high penetration resistant (HPR) material (Kay and Pickard, 1973). In the architectural sector, the polymeric interlayer can be known as an Anti-Shatter Film or ASF (Watch and Perkins, 2008). In the automotive industry the standard thickness of the PVB interlayer is 0.76 mm, whereas in the architectural industry the interlayer is usually supplied between 0.38 mm and 2.28 mm. The molecular weight of PVB is much lower than that of glass; the density of glass is around 2500 kg/m³ whereas the density of PVB is around 101 kg/m³ (Callister, 2007; Zang, Lei and Wang, 2007).

PVB is widely used in glass-polymer laminates due to its useful mechanical properties, its strong bonding to glass and its optical clarity. It is a non-toxic and non-corrosive resin that provides an excellent resistance to impact due to its high elongation to failure (MotoChem, 2009). PVB is a very tough material that helps disperse energy, restrict crack propagation and retain glass fragments during impact. As with any polymer, PVB is strain rate dependent. At low strains, PVB acts as a rubbery elastic with low stiffness whereas at high strains PVB acts as a stiff, glassy linear elastic material (Du Bois, Kolling and Fassnacht, 2003).

Many authors have reported a variety of modulus and strength values and experimental data has a large degree of scatter. For the purpose of this research, high strain rate data is considered to be the most appropriate.

PVB is an organic thermoplastic polymer that comes from the polyvinyl acetal group. It is made from polyvinyl alcohol by the chemical reaction between its hydroxyl groups and butyraldehyde. The PVB is then mixed with a variety of plasticisers. The chemical structure and bonding mechanism of PVB can be found in Figure 6 and Figure 7 respectively. The composition of MotoChem (2009) Polyvinyl Butyral resin can be found in Appendix C.

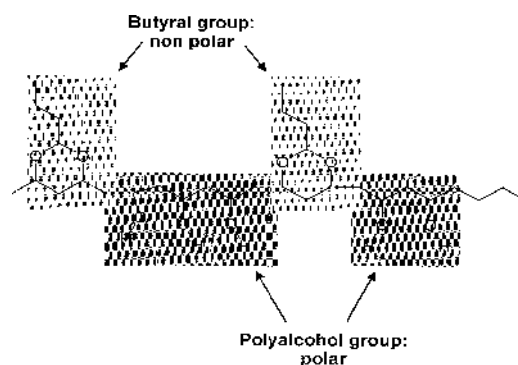


Figure 6. The chemical structure of PVB. (Taken from Keller and Mortelmans, 1999).

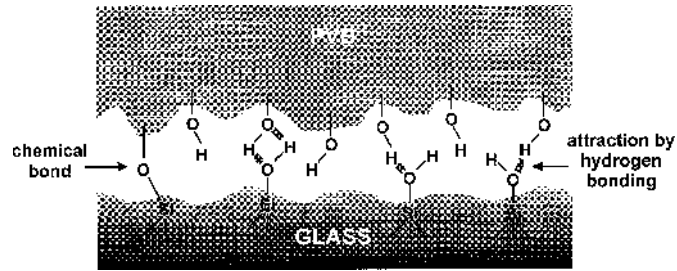


Figure 7. PVB-Glass bonding mechanism. (Taken from Keller and Mortelmans, 1999).

The polymer must be stored below freezing to prevent degradation. DuPont (2006) advise their customers to refrigerate PVB between 2°C and 10°C or interleave the PVB between poly ethane sheets.

Huntsberger (1981) found that the performance of windscreens (during impact) can be optimised by controlling the amount of delamination between the glass and the interlayer. If the bond strength between the glass and interlayer is too great, the possibility of occupant ejection in a crash situation increases. Whereas, limited bonding somewhat reduces the possibility of occupant ejection. This is due to the structure being more compliant thus absorbing more energy (Flocker and Dharani, 1998). If the vehicle is able to absorb a greater amount of energy during a crash, a lesser amount of energy is transferred to the occupant; thus minimising the possibility of injury. The bond strength can be controlled during manufacture. The PVB manufacturer, DuPont (2006), is able to supply the interlayer with either a smooth, universal or rough surface which partially controls the amount of delamination (DuPont, 2006).

2.2.4 Additional Manufacturing Processes of Laminated Glass

Further manufacturing processes offered by glass manufacturers include edgework (i.e. polishing and bevelling), colouring or tinting, screen printing, shaping and coating. Specially manufactured shapes requiring drill holes or cut-outs can also be processed; however this can be at the expense of the materials strength. Although edgework is usually deemed to be a compulsory process to remove sharp edges, it also makes the glass more aesthetically pleasing. Coatings are usually used for ease of cleaning, abrasive resistance or

to further retain glass fragments. The tin-side of float glass can also be easily processed into a highly reflective glass pane or a mirror.

2.2.5 Applications of Laminated Safety Glass

The design requirements of laminated glass, according to Bennison *et al* (2000), are based on the low probability of the glass cracking; deflection requirements (wind and snow in architectural glass); resistance to impact from projectiles and whether or not a cracked plate provides sufficient performance during subsequent loading. Major benefits of laminated glass include safety, security and an improved optical clarity post failure. Over recent years laminated glass has been used as a structural part of a modern buildings integrity.

Acoustic, Solar/Thermal and Dirt Reduction Applications – Environmental comfort in buildings is of fundamental importance. The sound reducing characteristics of laminated glass can help dampen and reduce excessive noise. The PVB interlayer acts as a filter to help reduce excess noise, creating a more pleasant environment. Two or more interlayers could be used to minimise noise pollution whilst still maintaining high optical quality. Solar control can be gained by adding a tinted interlayer which will limit the amount of interlayer degradation caused by direct contact with ultra-violet light. Coatings can also be used for further glass shard retention or as a self cleaning mechanism.

Road, Rail and Marine Applications – In the automotive sector, soda-lime-silica float glass (in the annealed state) is combined with a thin High Penetration Resistant (HPR) layer (typically 0.76 mm) of polyvinyl butyral (PVB) to form a 3-ply glass/PVB/glass structure known as laminated safety glass. The PVB interlayer helps retain optical clarity in the event of fracture as well as absorbing shock and preventing crack propagation (Iwasaki *et al*, 2007). As defined by Kay and Pickard (1973), windscreen performance depends on head deceleration performance; lacerative potential; resistance to penetration by head impact and stone impact (the glass should not self-propagate or craze); insensitivity of

product properties to the effect of normal handling and abrasion and insensitivity of product properties to extremes of temperatures. Following a vehicle collision, it is important that both plies of the laminated glass fracture to help dissipate the impact energy (Flocker and Dharani, 1997a). The PVB then acts to retain glass fragments, thus minimising the potential injury to vehicle occupants. Huntsberger (1981) reported that “penetration is prevented by absorbing the impact energy through stretching the PVB interlayer and skull fracture is prevented by reducing the thickness of the glass plies”. Furthermore, a reduction in glass thickness can lead to a significant reduction in the overall vehicle mass, increasing economical output. Glass contributes between 4% and 5% of the total weight of a vehicle and around 5% of a buildings total weight (CHAMP, 2009). The glass windscreen, side windows and rear window are a fundamental part of the overall stiffness of the vehicle (Sun, Andrieus and Ockewitz, 2005). The key is to reduce the mass whilst maintaining impact resistance and other beneficial properties (Grant *et al*, 1998). More recently laminated glass has been used for vehicle roofs to protect occupants in the event of a rollover. As stated by Zhao *et al* (2006) “the use of laminated glass in rear and side windows is rapidly increasing in new automobiles”. The use of laminated glass is also rapidly increasing in the bus, coach and rail industries and is increasingly being used in the prestige marine industry (Hogg, 2009).

Architectural and Construction – In order to address the regulations and standards of the architectural sector, the use of laminated glass in high rise buildings helps eliminate the serious danger of falling glass (Jacob, 2003). This safety feature is often mandatory in many public buildings and some residential buildings. The most obvious and common use for laminated glass is in the windows of buildings. Historically, the use of glass as a part of a buildings structural integrity was inconceivable; however, in regards to structural integrity, the use of modern architectural laminated glass is almost limitless. This has further allowed architects to use laminated glass in the design of roofs, skylights, canopies, facades, partitions, balustrades, store fronts, floors and stairs. Research has been conducted in the areas of severe weather

resistance, high security and safety (resistance to fire arms, bomb blasts and vandalism), fire resistance, insulation and electrically-heatable glass. One major area of research is with the effect of holes, notches and cut-outs that are manufactured into laminated glass thus severely reducing the strength of the material.

Upon impact, it is desired that laminated architectural glass fractures only at the outer ply; thus retaining the building integrity and allowing for replacement of the glass at the convenience of the owner with minimal disruption to the buildings occupants. "If the inside ply also fractures, window strength is significantly reduced to the point where wind and/or heating, ventilation and air conditioning loads can cause rapid collapse of the window" (Flocker and Dharani, 1998). Dharani and Ji (1998) investigated the possible use of two interlayers (i.e. glass/PVB/glass/PVB/glass) for the architectural sector. It was concluded that the cost of five-layer laminated glass units strongly outweighed the impact resistance performance and therefore is not recommended for use in the architectural industry.

2.2.6 Recycling Glass

With the exception of high quality automotive glazing, recycled glass or glass cullet is regularly used in the manufacture of commercial float glass. Laminated glass is recycled by crushing the glass into cullet and separating the plastic interlayer flakes (CHAMP, 2009). Cullet is crushed glass that is usually recycled from household items such as bottles and jars. The glass is treated, crushed and then sold on to glass manufacturers. Cullet usually makes up around 10-20% of the mixture of material used for the manufacture of float glass (Independent Glass, 2009).

2.3. Fracture and Failure of Laminated Glass

When subjected to point loading or impact, glass initially fails when the maximum tensile stress has exceeded the tensile strength of the non-impacted pane of laminated glass. At a critical load cracks open and extend in the glass surface at the location of the maximum tensile stress (Dharani and Ji, 1998;

Zhao *et al.*, 2006). Reaching the maximum principle compressive stress is likely to cause the crushing of the glass during impact (Dharani and Ji, 1998). However, the statistical nature of fracture and stress distributions in laminated glass are complex; this makes the prediction of the fracture and failure of the glass difficult. This is mainly due to the viscoelastic nature of the interlayer and the modulus mismatch between the interlayer and the glass. As stated by Vallabhan *et al.* (1997), the glass plates behave non-linearly creating very complex stress distributions in the sealants. The variability in the strength of laminated glass and the randomly introduced Griffith flaws also make the prediction of this glass difficult. Further to this, the large differences in modulus between the PVB ($E_{PVB}=10^6$) and glass ($E_{glass}=10^{10}$) make material behaviour prediction complex (Bennison, Jagota and Smith, 1999). In fact, the stiffness of the PVB interlayer is considered to be negligible in comparison with the stiffness of the glass (Zhao *et al.* 2006). The mechanical properties that control crack initiation include the strength of the glass, elastic properties of the glass and the visco-elastic properties of the interlayer (Bennison, Jagota and Smith, 1999). The fracture pattern is determined by the glass strength and randomly introduced Griffiths flaws of varying severity. It has been reported that the PVB interlayer fails by void formation coalescence (Hui *et al.*, 2003).

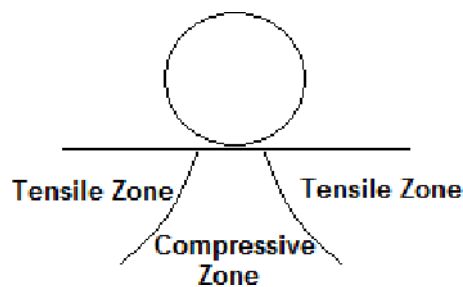


Figure 8. Compressive and Tensile zones on impact of a spherical indenter on a brittle material.

Xu and Li (2009) reported that shear stress causes plastic deformation; compressive stress causes radial cracks and tensile stress causes circumferential cracks.



Figure 9. Radial and circumferential crack patterns in laminated glass.

The fracture characteristics of glass during impact are largely dependent on projectile size, projectile velocity, projectile construction and material and the mechanical properties of the glass (Kaufmann *et al*, 2002).

2.3.1 Wave Propagation

Flocker and Dharani (1998) and Grant *et al* (1998), investigated finite element wave propagation codes to determine the stresses caused by impact to laminated glass. The wave propagation algorithms were used to model the effect of delamination. The model can be used to control the amount of delamination in order to optimise laminated safety glass. The model can be further used for multilayered laminated glass systems where the amount of delamination between the adhesive and glass can be predicted.

2.3.2 Fracture Characteristics

The strength of a brittle material is largely determined by defects that lie in the surface of the material. The sizes of these defects govern the ease at which crack initiation can occur and subsequently grow. Cracks are fairly difficult to initiate but will propagate easily when started. “As the applied force is increased the tensile stresses on the cracks increase proportionally until one of the cracks propagates along the circular principle stress trajectory to form a ring crack” (Wilshaw, 1971). Other types of cracks that are apparent when a brittle material is subjected to impact by a spherical indenter include cone, median, lateral and radial cracks (Flocker and Dharani, 1997a). An in-depth

morphological description of each of these crack types is reported in the work of Cook and Pharr (1990). The Hertzian cone crack will be described further in section 2.3.4. Grant *et al* (1998) refer to the different types of cracks as surface scratch or crushing; star cracks; cone cracks; or a mixture of cone and star cracks.

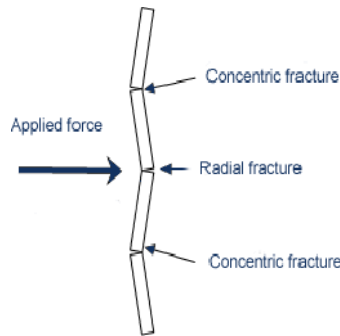


Figure 10. Radial fracture (failure in tension) and Concentric fracture (failure in compression). (Taken from Jones, 2002).

It has been reported that the initial contact by a hemispherical impactor will be at a single point transforming into a disc (Geandier, Denis and Mocellin, 2003). The point of initiation is assumed to be where the cone crack meets the PVB interface where the stresses are highest (Huntsberger, 1981).

As reported by Dharani and Ji (1998), initial damage to the laminated glass is caused by large compressive stresses at the outer ply (the impact side of laminated glass) at the impact area. A high impact velocity will cause greater damage to the impact area as the glass becomes crushed. If the velocity is high enough at impact, Hertzian Cone cracks form in the outer ply; this will be discussed further in section 2.3.4. Hertzian Cone cracking was also observed by Ball and McKenzie (1994) when researching monolithic glass plates. Previous research has also found that, during Hertzian indentation, a surface ring crack forms at the circumference of the contact area, followed by a cone crack extended into the structure (Xi and Lu, 2009).

Bennison, Jagota and Smith (1999) and Zhao *et al* (2006) broadly reported that the fracture and failure of laminated glass occurs in the following order;

1. Cracking in the glass directly beneath the impact area of the impacted ply.
2. Rapid fragmentation of both glass plies.
3. Stretching, deformation and rupture of the polymer interlayer with associated interfacial debonding.

For small deformations, the elastic response of the material is determined by the glass whereas for large deformations (i.e. a crash situation/impact) the PVB plays a dominant role due to the fact the glass cannot withstand large strains (Du Bois, Kolling and Fassnacht, 2003). Therefore if the glass layers fail the PVB acts as a membrane to retain glass fragments.

Flocker and Dharani (1998) reported that crack initiation occurs between 0.62 μs and 1.5 μs after the contact between the projectile and glass surface. The crack then propagates through the outer glass ply at a velocity of 1550 m/s with a cone angle of 30°. An elliptical cone angle of $24^\circ \pm 2^\circ$ has also been reported (Geandier, Denis and Mocellin, 2003). Grant *et al* (1998) found a clear relationship between the thickness of asymmetric laminated glass and the lowest velocity at which damage occurs, V_{crit} .

2.3.3 Wallner Lines

Wallner (1939) showed that “the interaction of the propagating crack with shear waves emanated from the fracture can lead to characteristic undulations on the fracture surface”. These lines, known as Wallner lines, can be used to determine local crack speed and are easily visible due to the light reflected from the smooth fracture surface as seen in Figure 11.

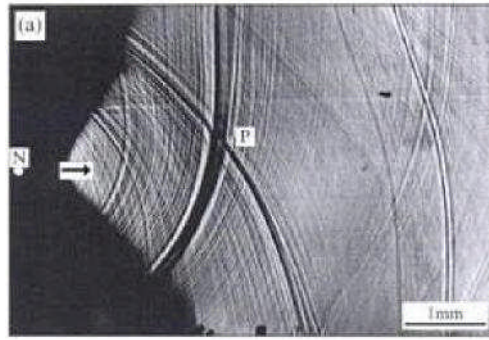


Figure 11. Wallner lines on the fracture surface of an inorganic glass. Point N is where crack initiation occurs. Point P is where the crack propagation speed is measured ($P=0.26 C_s$). (Taken from Hull, 1999).

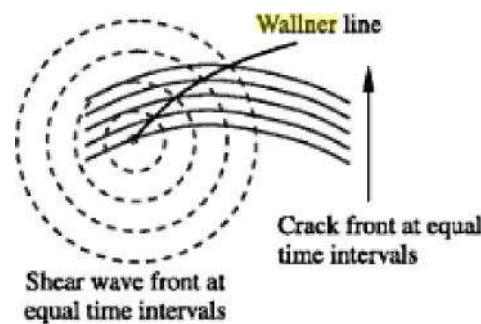


Figure 12. Schematic representation of the formation of Wallner lines through the interaction of the propagating crack front with a shear wave created from a perturbation along the crack. (Taken from Ravi-Chandar, 2004).

Wallner (1939) also reported that these lines have been found in many brittle materials including glass.

2.3.4 Hertzian Fracture

The Hertzian Cone Fracture was first discovered by Hertz in 1881 and is usually caused by the impact of a spherical indenter on an isotropic brittle solid. It is thought that cone cracks are caused by microdefects at the surface of brittle materials. As reported by several authors, cone crack formation appears during unloading (Geandier, Denis and Mocellin, 2003; Johnson *et al*, 1973). The Hertzian test can be used to characterise materials in order to help predict the failure of brittle materials such as glass. This test gives three important material properties: (i) the fracture toughness of near surface material; (ii) densities of

surface crack sizes; (iii) and, residual stresses in near surface material (Wilshaw, 1971).

The Hertzian prediction of fracture indentation is an accurate description of the stress field induced by an impactor. However, this prediction assumes that the impactor takes place without the influence of friction (Jelagin and Larsson, 2008).

2.3.5 Adhesion, Delamination and Friction

Delamination is when the layers of a composite material separate at the interface between the layers. This is largely determined by the strength of the adhesive. The delamination or adhesive strength of laminated glass is of critical importance and is used to balance its performance properties (Sha *et al*, 1997). Poor adhesion will lead to separation between the glass and interlayer whereas too high an adhesive strength leads to a reduction in impact strength. If the adhesion strength is too high, the interlayer is unable to stretch which compromises its impact strength. Therefore lower adhesion strength is desired, which will allow a larger deformation of the interlayer, thus helping dissipate impact energy. Laminated glass is usually manufactured with medium adhesive strength so that the glass retention and impact strength are optimised (Sha *et al*, 1997).

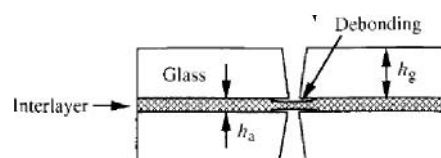


Figure 13. Tension adhesion test showing area of debonding. (Taken from Sha *et al*, 1997).

The research of Huntsberger (1981) found that the PVB interlayer stretches in order to absorb the kinetic energy transferred through impact. Kinetic energy is further absorbed through the partial delamination between the layers. High velocity impact will crush both glass layers causing the PVB to rupture. Debonding propagates away from the crack initiation location where “debonding at the interface is based on the primary assumption that debonding is a

propagating phenomenon” (Flocker and Dharani, 1998). The strength of adhesion between the glass and interlayer is of utmost importance (Sha *et al*., 1997).

2.3.6 Factors Influencing the Properties of Laminated Glass

The large differences in stiffness between the glass and PVB make assessment by analytical means virtually impossible due to the complex stress fields (see section 2.3.). Therefore, the most economical method of predicting the failure of laminated glass is by using techniques such as finite element analysis or continuum to non-continuum FEA. An example of this is the element deleting method, whereby elements are deleted when certain criterion are met. Other methods include smooth particle hydrodynamics (a discrete-particle algorithm) or other meshless varieties of numerical simulation.

The mechanical properties of laminated glass are highly dependent on the manufacturer of the glass and PVB, glass composition, batch, raw material location and residual stress distribution (Hogg, 2009). Glass obtained from different suppliers or different batches may have different mechanical properties or surface residual stress distributions (Jelagin and Larsson, 2008). Static fatigue, which is a form of stress corrosion cracking, has been reported to cause slow crack growth prior to instability (Wilshaw, 1971).

PVB is also highly sensitive to temperature and moisture making its mechanical properties difficult to characterise. “The underlying molecular rearrangements that lead to the energy dissipation properties also give rise to rate and temperature dependent stiffness characteristics” (Bennison *et al*, 2000). The stiffness of PVB will decrease with an increase in temperature. An increase in temperature also makes the PVB extremely susceptible to creep and stress relaxation. At 60°C PVB is on the verge of disintegration (Belis *et al*., 2007). “The shear modulus of PVB evaluated from the experimental data decreases about two orders of magnitude in the temperature range between -20°C and +40°C” (Kruger, 1998). PVB is highly sensitive to moisture which is dependent on the environmental relative humidity. “Laminated safety glass interfacial

regions comprise of thin aqueous layers lying between the glass and interlayer even at a relatively low humidity” (Huntsberger, 1981). The moisture content can also be dependent on contaminants that may be present before construction. The quality of water and subsequently, the cleaning process, can also affect the bond strength between the PVB and glass layers. The bonding mechanism between glass and PVB is highly complex which is mainly due to the adhesion level being largely affected by minor variations in quality, treatment of glass and conditioning of PVB (Keller and Mortelmans, 1999).

Le Bourhis and Metayer (2000) reported that the presence of tin near the surface of the glass can modify its mechanical properties. This theory is based on the thought that there are tin impurities found in the lower surface of the glass infused during the float process. Bennison, Jagota and Smith (1999) reported that the construction of laminated glass should be symmetrical, for example the 3-ply construction should be constructed so that the air side of the glass faces outward from the PVB interlayer (air-tin/PVB/tin-air). Bao and Gao (2008) reported results that indicated the strength of the air side was higher than that of the tin side caused by a difference in surface roughness or micro-defects. It has been report by Gorokhovskiy and Matasov (2000) that the adhesive strength of the air-side surface of the glass to the PVB interlayer is lower in comparison to the tin-side. It has also been claimed that the strength of the tin-side is around 0.9 - 1.0% lower than that of the air side due to additional micro-cracks found on the tin-side surface (Bao and Gao, 2008). Bennison, Jagota and Smith (1999) found that first cracking occurs at the glass tin-side PVB interface due to the characteristic strength difference. It has further been reported that the air side hardness can be up to 10% greater than the tin side (Howell, Hellmann and Muhlstein, 2008). Therefore, the tin side of the glass would be more susceptible to scratching during manufacture, transportation and handling

As with any polymer, PVB is highly sensitive to strain rate. High strain rate can change the modulus and tensile strength of PVB (Zang, Lei and Wang, 2007). The aforementioned authors took the modulus and tensile strength of PVB to be

100 MPa and 18.62 MPa respectively. However, the strength of the glass-PVB interface under high strain rates is not yet established enough (Iwasaki *et al*, 2007).

24 Modelling Techniques

Finite element models are relatively easy to manipulate and post-processing provides consistent results, thus saving time and cost. A reliable model also has the ability to be adapted to provide results for prototypes or redesigns. On the other hand, experimental testing produces real data that can be relied upon. However, experimental testing can be time consuming and costly as well as possibly producing a large scatter of results. Undoubtedly, the most effective material laws are based on tabulated stress-strain curves obtained directly from physical testing (Du Bois *et al*, 2006). As with any numerical model, many assumptions are made. The key to generating an economic computer simulation is to find the balance between an accurate representation of the components behaviour whilst maintaining some degree of computational efficiency (Livermore Software Technology Corporation, 1997). “Although experimental testing is always necessary, there is a considerable motivation for the development and validation of numerical models in this area” (Livermore Software Technology Corporation, 1997).

Optimisation of the model plays a vital role in reducing the computational power, machine time and memory usage (Zhao *et al*, 2006). However, it is also important to stabilise the model to ensure further mesh refinement has a minimal effect on the resultant data of interest; it is for this reason that a convergence study should be implemented. Ideally, the mesh should be refined around the impacted area in order to better capture the dynamic response of laminated glass (Zhao *et al*, 2006). In order to save computational power and limit solve time, the majority of authors modelled a quarter of the laminated glass and impactor making the assumption that the model is symmetrical. However, the smallest time step is dependent on the smallest element, thus decreasing the element size will result in a longer processing time.

The most effective method of determining local stress intensity factors or energy release rates would use a finite element method whereby the mesh is actively refined at every crack tip (Jagota and Bennison, 1995). This method would help define the fractography and crack propagation properties. However, even with modern computational power, this method requires a huge amount of detail in regards to the microstructural features. Jagota and Bennison (1995) found that the most productive and efficient method of simulating crack propagation was to use an element deleting rule. This method is based on element removal, element fragmentation and separation of element boundaries dependent on predefined stress, strain or energy criterion.

For simplicity, many authors have considered the interlayer to be incompressible with a Poisson's ratio of 0.5 (Sha *et al.*, 2007; Du Bois, Kolling and Fassnacht, 2003; Du Bois *et al.*, 2006; Timmel *et al.*, 2007). Geandier, Denis and Mocellin (2003) used a friction co-efficient value of 0.1 between the steel indenter and glass surface. Jelagin and Larsson (2008) used a friction co-efficient value of 0.12 ± 0.025 that was reported to be in good agreement with experimental observations. Du Bois, Kolling and Fassnacht (2003) used MAT_32: Laminated Glass Model of LS-DYNA to model a laminated glass windscreen. The authors used a failure strain of 0.1% for the glass and no failure for the interlayer (Du Bois, Kolling and Fassnacht, 2003; Timmel *et al.*, 2007). This model is based on the theory that when the glass fails, the load is taken purely by the PVB interlayer. Rate dependence is neglected during this study. These effects are also neglected in the research conducted by Timmel *et al.* (2007). Previous work is still restricted by simplifying assumptions (Duser, Jagota and Bennison, 1999).

Flocker and Dharani (1997b) simplified the prediction with no interlayer debonding or slipping between layers during impact. The aforementioned authors used four-node quad elements with a Gauss integration rule and hourglass control to model the response of laminated glass subjected to dynamic loading. Hourglass control is used to eliminate zero energy displacement nodes; this is detectable using the software LS-DYNA (Flocker

and Dharani, 1997a). Flocker and Dharani (1997a) also used non-reflecting boundaries assuming that wave propagation was negligible. Convergence was within 4%. Flocker and Dharani (1998) later modelled the glass plies and steel impactor as linear elastic materials in order to try and understand the elastic properties of the materials.

The PVB interlayer should be considered to be elastic or linear visco-elastic when impacted by a small projectile at high velocity. At low velocity the PVB interlayer should be modelled as a viscoelastic or hyperelastic material (Iwasaki *et al*, 2007). Plasticised PVB can be accurately characterised as a linear viscoelastic material (Ferry, 1980). However, the research concluded that it is unsatisfactory to neglect these effects and their effects have to be considered in future research.

Zang, Wei and Wang (2007) researched the use of continuum to non-continuum mechanics (discrete element method) to model the response of laminated glass when subjected to impact. A comparison of FEA and the discrete element method (DEM) was undertaken and it was found that for the elastic calculations, DEM agrees with FEA data (Zang, Wei and Wang, 2007).

Analytical results from Dharani and Ji (1998) showed that the probability of fracture in the outer glass layer is strongly dependent on the impact velocity, slightly on glass ply thickness and marginally on the interlayer thickness. Dharani and Ji (1998) modelled 60° of a 100 mm diameter circular laminated glass plate under biaxial flexure. The glass panes were modelled as a linear-elastic material and the PVB modelled as a linear viscoelastic material. “Many polymers follow this linear viscoelastic law very well especially when strains are small as in the case of laminated glass subject to low velocity impact” (Fung, 1965). It has been reported that impacting larger laminated glass samples results in lower principle stress due to the increase in flexibility of the sample (Zhao *et al*, 2006).

Du Bois, Kolling and Fassnacht (2003) modelled the impact of laminated glass using Belytschko-Tsai shell elements for the glass and membrane elements for

the hyperelastic PVB interlayer. The shell elements, representing the glass layers, are removed from the calculations once they fail. The glass was modelled with linear piecewise plasticity which allows a small plastic strain before failure (Du Bois, Kolling and Fassnacht, 2003). Du Bois *et al* (2006) later used the elastic-plastic MAT_24: Piecewise Linear Plasticity Model of LS-DYNA coupled with MAT_182: Simplified Rubber Model with hyperelastic-viscoelastic laws for the elastomer interlayer. The stress distributions through the thickness of laminated glass were shown to be dependent on the PVB shear modulus (Du Bois *et al*, 2006; Wei, Shetty and Dharani, 2006).

Zhao *et al* (2006) studied high impact velocity (6.67 m/s) of a spherical indenter on laminated glass. The author used eight-node linear brick elements with reduced integration and hourglass control. Timmel *et al* (2007) used a smeared modelling technique to compute the change of acceleration of an impactor. If the glass does not fail, the composite acts like a shell i.e. it is able to transmit normal forces and bending moments. If the glass fails, only the interlayer is able to carry loads i.e. it acts as a membrane.

2.4.1 Model Validation

Previous authors have discussed three methods in which to attempt to characterise the fracture and failure of laminated glass when subjected to impact loading. These are experimental testing, theoretical and statistically based testing (e.g. Weibull) and finally numerical simulation such as FEA.

Research in the area of laminated glass dates back to around 1973 when Kay and Pickard performed headform impact testing on a new 'Triplex Twenty-Ten' laminated glass windscreen. The aim of the research was to reduce facial laceration and optimise the headform deceleration. The results taken from this research were maximum deceleration due to glass (g); duration of deceleration due to glass (ms); maximum deceleration due to interlayer (g); total duration of impact (ms) and whether there was full penetration of the laminated glass. It has been recommended that authors should attempt to model laminated glass followed by model validation using experimental data (Timmel *et al*, 2007).

Prior to experimental testing, it has been suggested that the indenter should be cleaned with soap water and acetone (Jelagin and Larsson, 2008). It has been reported by Wei *et al* (2006) that no dynamical experimental data is available for impact testing corresponding to a square laminated glass plate. Therefore Wei *et al* (2006) used the static analysis results from Vallabhan *et al* (1993) for validation.

Many authors have used statistical analysis in order to predict the failure of materials such as laminated glass. This prediction can then be used as a validation for numerical simulation. The Weibull statistics can predict both the size and distribution of surface flaws in order to aid material characterisation (Fischer-Cripps, 2007; Weibull, 1939). "In general, Weibull's probability distribution is very useful for characterising the probability of failure or damage in glass-like brittle materials" (Flocker and Dharani, 1998). Uniform tensile stress can be calculated using the Weibull statistical analysis based on the probability of failure of a specimen with a predefined surface area. The failure prediction is based on the probability of Hertzian cone crack initiation (Fischer-Cripps, 2007).

2.5. Standards

There are many standards relating to industry specific testing; this research will mainly focus on impact specific and road transport standards. A short overview of the most significant standards is given below.

BS 857:1967 specifies the requirements and test procedures for safety glass used in land transport. The standard defines three test methods, a fragmentation type impact test, a high performance impact test and an adhesion strength test. The fragmentation test replicates a stone impact. The hemispherical steel impactor (mass = 0.227 kg, diameter = 3.8 cm) is dropped from a height of 9.15 meters onto the centre of a supported 30.5 cm² glass sample. The high performance impact test uses a hemispherical 2.27 kg impactor with a diameter of 8.25 cm. The impactor is dropped from a height of 3.65 m onto the centre of a 30.5 cm² laminated glass sample. For both tests,

the glass is unsupported on a 29 cm² (inner area) wooden frame bolted to a steel frame. Prior to testing, the glass should remain in an ambient temperature of 25°C ± 4°C for a duration of four hours to ensure the temperature is uniformly distributed throughout the glass.

In 1992, BS AU 178a - 'Road vehicle safety glass' was introduced specifically for road vehicles. In regards to the impact test setup and procedure, this standard is very similar to BS 857. The subtle differences include a rubber gasket (hardness 50 IRHD) to prevent shock and replication of the test six times rather than three. The test coupons are to be 300 mm² laminated glass samples and between 2.1 mm and 6.2 mm thick. BS AU 178a specifies that road vehicles may have either untreated laminated glass or treated laminated glass. The glass must have at least one layer that has been treated in order to increase mechanical strength and condition fragmentation after shattering. The international standard, ISO 3537:1999, also specifies the safety requirements for laminated glass used in road vehicles. The standard specifies ambient temperature, atmospheric pressure and relative humidity. This standard is virtually identical to BS AU 178a.

BS EN 356:2000 is the British/European standard used in the construction and architecture industries. A 1.10 m by 0.90 m test piece is subjected to dynamic loading caused by a 4.11 kg steel sphere (diameter 100 mm) dropped from a specified height. This height is dependent on the 'category of resistance' (i.e. the amount of force the product should resist or how safety critical a building is). Some international laminated glass manufacturers also use the ASTM standard C 1172 – Specification for laminated architectural flat glass, which is similar BS EN 356. Finally, the delamination or adhesion strength can be tested using the industry standard peel test, pummel test or tension adhesion test (Sha *et al*, 1997).

2.6. Literature Overviews and Conclusions

Many attempts have been made to model laminated glass with a varying degree of success. Due to the high complexity of the stress fields witnessed during an

impact situation, modelling of laminated glass has previously proven to be a difficult task (Bennison, Jagota and Smith, 1999). The large difference in modulus and complex failure mechanisms make the characterisation of glass and PVB difficult. Previous attempts at modelling laminated glass have made several assumptions with regards to material characterisation thus limiting model validity.

Material Characterisation

The following material characterisation will be broadly based on the material properties required by MAT_32 material model of LS-DYNA.

3.1 Glass Characterisation

The Laminated Glass Model (MAT_32) of LS-DYNA is based on the theory that, in the elastic range of laminated glass the stiffness of the material is purely dependent on the stiffness of the glass. Post glass failure, the stiffness of the laminated glass is purely dependent on the stiffness of the PVB interlayer.

The initial material properties used in this model are taken straight from the literature as a baseline. Ideally, the author would have conducted mechanical testing in order to gain a better understanding of the material characteristics. The material properties gained from this testing would have then been used for the material properties found in the numerical simulation. It was initially planned that mechanical testing could also be conducted for the 200 mm² 3 mm thick annealed float glass, however due to the failure of equipment the project was set back and no time remained for this.

Material characterisation of the PVB proved extremely difficult. This was due to the fact that the chemical structure of the PVB changes during processing. An attempt was made at processing laminated glass with an 'overhang' of PVB so that it remains in the processed state but free from the glass. Manufacturing this was proved extremely difficult as the PVB folded back on itself and became fixed due to its high level of adhesion. However, the PVB manufacturers DuPont are able to manufacture laminated glass this way. Due to the limited time, no mechanical testing could be conducted for the PVB interlayer.

3.1.1 The Properties of Glass

MAT_32 requires the following material properties: Young's modulus; Poisson's ratio; yield/proof stress; plastic hardening modulus; plastic strain at failure. These properties were initially taken from the literature (Callister, 2007) in the hope that mechanical testing would be conducted later in the project.

3.1.2 The Properties of PVB

MAT_32 requires the following materials properties for the polymer interlayer: Young's modulus; Poisson's ratio; yield/proof stress; plastic hardening modulus. The material properties for the PVB were also taken from the literature (Zang, Wei and Wang, 2007); these values were chosen as they were deemed acceptable high strain data.

32 MAT_32 Material Parameters

As there are no units assigned in LS-DYNA, the end user must verify that all properties follow the consistent units guide (dimensions measured in millimetres) of the OASYS LS-DYNA3D: Users Guide (version 6.1) (Livermore Software Technology Corporation, 1997). All glass and steel properties are taken from Callister (2007) and PVB properties taken from Zang, Lei and Wang (2007).

Table 2. Material properties used for MAT_32. (Taken from Callister, 2007; Zang, Lei and Wang, 2007; Du Bois, Kolling and Fassnacht, 2003; Timmel *et al*, 2007).

Material	Dimensions			Mass	Material Properties					
	Length	Width	Thickness		Density	Youngs Modulus	Poissons Ratio	Proof Stress	Plastic Hardening Modulus	Plastic Strain at Failure
Soda-Lime Glass	200	200	6.0	-	2.50E-09	6.90E+04	0.23	34.6	1.00E-20	1.00E-03
Polyvinyl Butyral	200	200	0.4	-	1.01E-10	0.10	0.42	18.62	1.00E-20	-
Low Carbon Steel	Radius = 8.0 (Hemispherical)			0.00266	7.85E-09	2.07E+05	0.30	-	-	-

No failure criterion properties are given to the steel indenter as it is treated as a rigid material that will not deform. The plastic strain at failure/failure strain value of 0.1% was taken from Du Bois, Kolling and Fassnacht (2003) and Timmel *et al* (2007).

Mat_32 requires an average density of the polymer interlayer and the glass layers. As density is a measure of mass per dimension, the average density of the glass and PVB could be used. The average density of laminated glass is 1300.5 kg/m³ or 1.3005E-9 to agree with the input parameters of the model.

Numerical Simulation Methodology

The original experimental testing for validation was changed due to the failure of equipment (discussed further in Chapter 5). In regards to the modelling methodology, the glass samples and boundary conditions remained the same; however, the geometry of the indenter changed. Therefore, the first model was modified so that the indenter geometry matched the experimental setup. A considerable amount of time and effort was spent on the original simulation and therefore the methodology of which is discussed in the following. The results of the second model are reported in the results section of this research (n.b. – no results from the first model are reported as these were superseded by the results of the second model). Hypermesh software was used to construct the geometry of the model. It was decided that Hypermesh would be used due to its user-friendly interface and the ease at which new components can be constructed. Hypermesh also provides more advanced options with regards to meshing the components. The model was then exported to Primer; the highly compatible pre-processing software of LS-DYNA.

4.1 Pre-Processing Methodology

4.1.1 Hypermesh

Hypermesh is a pre and post-processing finite element program that has an easy-to-use interface for 2D and 3D model creation. Hypermesh is compatible with a vast amount of commercially recognised finite element solvers.

Creating the geometry for the model 1 impactor was fairly complex as its profile was irregular. The profile of the indenter was not hemispherical; therefore the simple radius-creation function could not be used. Instead, a photograph (Figure 14) of the indenter was taken and, using a co-ordinate system twenty-four points were created to define the profile of the indenter (Figure 15). The points (or temporary nodal points, as defined by Hypermesh) were then joined using the line function.

Shell elements are used as the width of the laminated glass is much greater than its thickness. A 200 mm² surface was created to represent the mid plane of the laminated glass. Using the automesh function, a mesh with an element size of 5 mm was created so that boundary conditions could be easily added using Primer. The elements were four-node quadrilateral shell elements.



Figure 14. Original test impactor with reference scale.

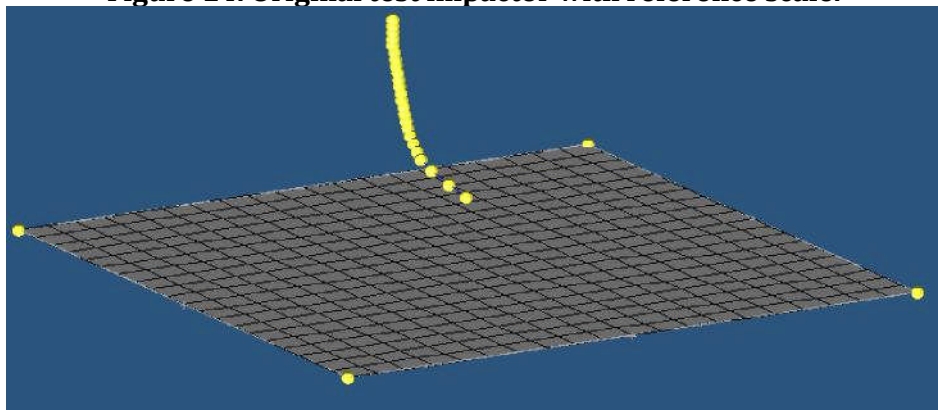


Figure 15. Hypermesh (Model 1) - 5 mm element meshed glass and 24 point impactor profile.

The spin function was then used to rotate the impactor line through 360° about the Z axis (vertical). The impactor was then scaled to the correct size (in millimetres) and the surface meshed (Figure 16).

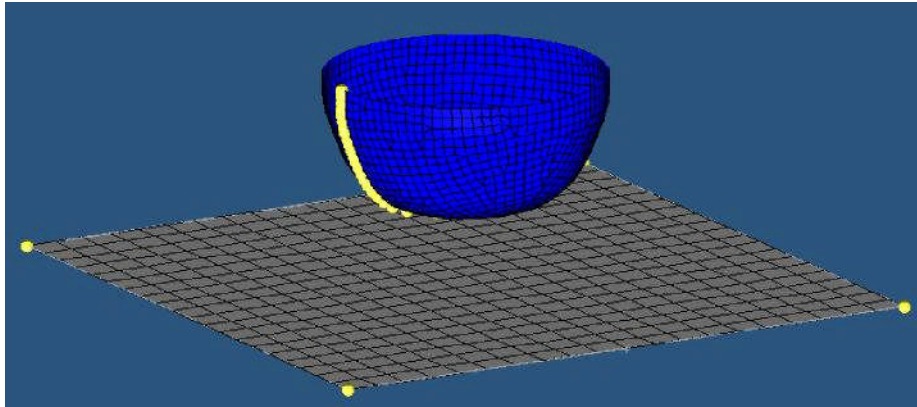


Figure 16. Glass and impactor geometry created using Hypermesh (Model 2).

The model was then exported as a keyword file and imported into Primer.

A second model was created (Model 2) with the simpler hemispherical geometry of the impactor found in the second experimental setup. Due to the failure of equipment the model geometry was modified to fit the new test parameters found in Section 5.3. The geometry for the glass component of the model remained the same. Using Hypermesh, a new hemispherical impactor was modelled that fully represented the impactor found on the Rosand Drop Tower. To create the new impactor, an arc of radius 8 mm was generated then rotated in the Z axis (vertical) to generate a surface. The impactor was then positioned using the translation function so that the impact would occur at the centre of the glass. The impactor was then meshed and the model was exported to Primer.

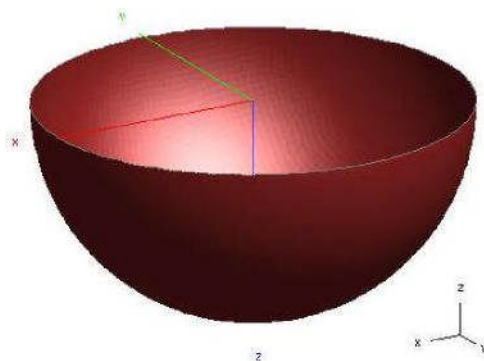


Figure 17. Model 2 hemispherical impactor (8 mm Radius).

4.1.2 Primer

The procedure described in the following was conducted for both models. The impactor and glass were separated into two parts and the shells given a thickness using the SECTION_SHELL keyword. The thickness for the glass was set at 6.4 mm (the same as the experimentally tested glass) and the steel impactor thickness was set at 0.1 mm. The steel impactor was set at this thickness as the material type was MAT_020: Rigid (a rigid body) and therefore would not deform. The shear factor and element type was left to the default of 1.0 and 0.0 (Belytschko-Tsai) respectively for both the impactor and the glass. Material properties defining the glass were then added with properties taken from the literature and reported in Table 2 (Zang, Lei and Wang, 2007; Callister, 2007). The material type was left as the default MAT_001: Elastic so that the model could first be validated (the material type would then later be changed to MAT_032: Laminated glass model). Inertia properties were given to the rigid body impactor so that the centre of mass, total mass and local inertia properties could be specified. The inertia properties for the impactor were set at a value of 1×10^6 in the XX, YY and ZZ axes so that no out of plane rotation of the impactor would occur during impact. As specified in the 'original testing regime', the impactors mass was recorded (2.17 kg) and specified in the PART card keyword file.

A node set was then created so that boundary conditions around the edge of the glass could be specified. Single point constraints were used so that the individual nodes could be constrained. Nodes within 25 mm of the edge of the glass were constrained about the Z direction and rotationally in the X and Y axes (Figure 18).

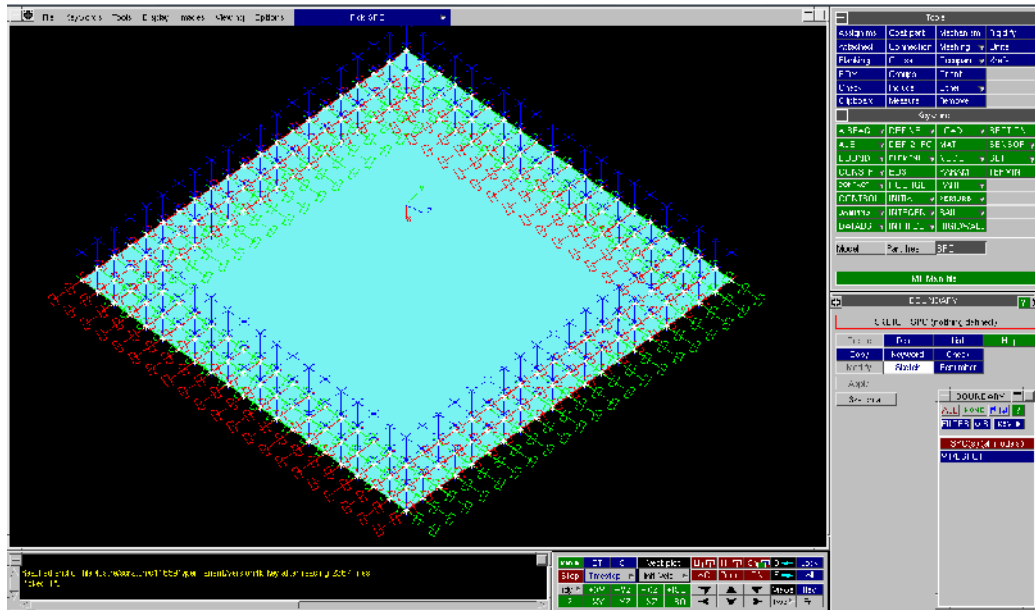


Figure 18. Screenshot of the original modelling boundary conditions.

A node was fully constrained to the impactor using the EXTRA_NODE function in the constraints keyword file. This node was positioned at the upper centre of the impactor and acted as the accelerometer. This extra node carried no additional mass. The accelerometer was then added using the extra constrained node and a local co-ordinate system was used to orient the axes of the accelerometer. This function allowed a history of the acceleration data (DATABASE_HISTORY_NODE keyword) to be stored from the simulation. The DATABASE_BINARY keyword also allowed the model to write a D3PLOT and T/HIS (time history) file.

An initial velocity (INITIAL_VELOCITY_RIGID_BODY keyword) was then generated so that the model could predict the deceleration once an impact velocity had been specified. The velocity was initially set at 1000 mm/s. The initial velocity would later be modified to fully replicate the impact velocities used in the experimental testing. The initial velocity was identical to the impact velocity as the model was set so that the impactor was not subject to the acceleration due to gravity. Finally, a sliding and tied (AUTOMATIC_SURFACE_TO_SURFACE) contact was defined using the CONTACT keyword. A shell set was created in the area that would be

contacted on the glass by the falling impactor so that the contact searching routines in the model were as economical as possible. As the vertically falling impactor would only contact elements in the glass directly below it, other elements outside this contact zone were eliminated from the time-consuming contact search routines, see Figure 19.

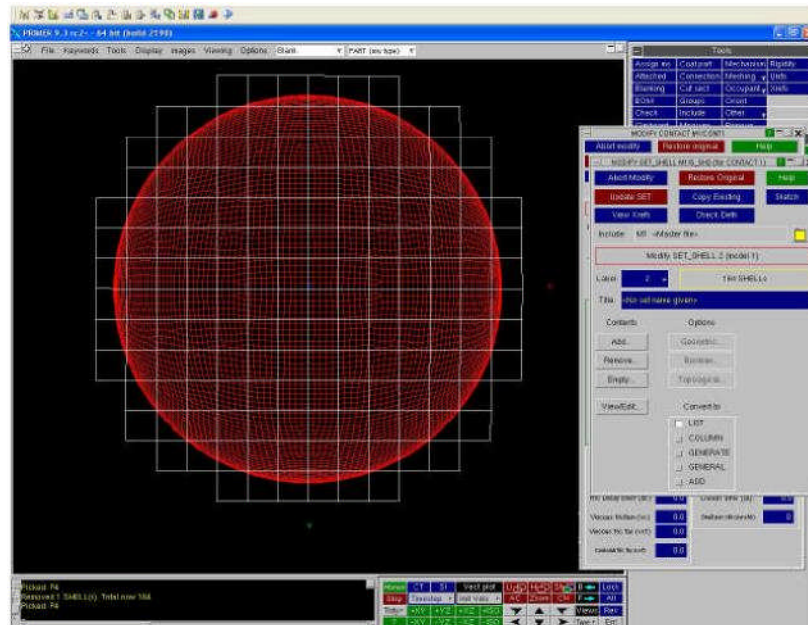


Figure 19. AUTOMATIC_SURFACE_TO_SURFACE Slide and Tied Contact.

As the glass elements were previously defined as shell elements, a penetration check was performed to ensure the impactor and glass were not already in contact with each other. Primer displays shell elements as the mid plane of the laminated glass; the thickness of the glass is not visible. This was done so that the impactor could be as close as possible to the glass without penetrating it. This was to ensure further computational efficiency. The model was set so that the default time step was used and a user defined termination time of 50 ms was set. The termination time was later modified so that the solving time could be decreased. The material model MAT_32: Laminated Glass was then added to the glass part card and the required material properties were entered.

Integration points in LS-DYNA are used to define thickness associated with shell elements. The shell elements are graphically displayed as the centre line of the component. For MAT_32, the laminated glass model, the integration

points are selected at the centre of each component. For example, the centre of the interlayer is defined so that the model recognises that this relates to the appropriate material definition found in the material card of LS-DYNA. In this example when $f_n = 1.0$, the model relates the associated thickness of the polymer material card and where $f_n = 0.0$ the glass material and thickness properties are used.

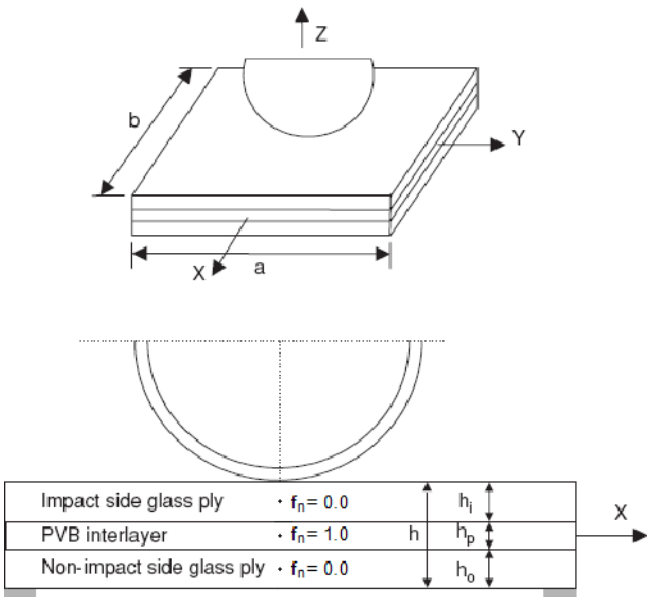


Figure 20. Schematic laminated glass construction with integration points defined.
(Adapted from Zhao *et al*, 2006).

Integration points were defined through the thickness of the laminated glass using the appropriate thicknesses and weighting factors – these points were used by the software to calculate stress and strain values through the glass. The model was checked for warnings or errors and duplicate or coincident nodes and then saved. The model was then modified so that it matched the impact velocities found in the experimental testing results. The interlayer bond was assumed to be perfect with no delamination or friction between the layers during impact.

4.1.3 Problems Encountered During Pre-Processing

As previously discussed, the model was modified so that it fully replicated the experimental testing using the Rosand Impact Tester. Once the model had

been modified, the mesh was refined so that better material behaviour was captured. Due to the mesh refinement, new boundary conditions and contact areas had to be defined in order to capture the response of the new nodes. This was initially neglected and nodes within the 'experimental constrained' (steel frame) area were unconstrained.

4.2. Post-Processing Explicit Finite Element Analysis

4.2.1 LS-DYNA (Solver)

LS-DYNA is a commercially available multi-purpose finite element program used across a variety of industries. Results found using LS-DYNA are also transferable to other solvers (Du Bois *et al*, 2006). Primer is the highly compatible pre-processing software component of LS-DYNA.

The numerical simulation was solved using the commercial dynamic nonlinear three-dimensional finite element code LS-DYNA developed by the Livermore Software Technology Corporation (1997). The solution times of each model varied depending on the individual model specifications and are reported in the results. Impact velocity, element size and contact area were the most sensitive parameters on controlling the solution time. All results reported were solved using double precision and four processors of the high performance ASTRAL computer system at Cranfield University. Once solved, the model was checked for hourglassing by recalling the solvers log file.

4.2.2 D3PLOT and T/HIS

D3PLOT software was used to determine the stress contours and fracture patterns of the laminated glass. Results for which can be found in Chapter 6.

T/HIS software was used for graphical correlation between the experimental and FE results. A C180 filtering code regularly used in the automotive industry was conducted on the raw data for the reasons of noise removal. Results taken from the experimental data were converted into comma separated variable (CSV) files and imported into T/HIS. To convert the FEA acceleration data from mm/s^2 into gravitational sensitivity (g) so that they could be correlated with the

experimental results, all data were divided by 9810 mm/s^2 . Correlations between the experimental data and numerical prediction can be found in Chapter 6.

4.3. Further Numerical Simulation

A convergence study was completed in order to optimise the model. The mesh was refined and the element size decreased using the basic mesh sub-division function in Primer. The size of the elements for the impactor remained the same when the glass elements were refined. The initial model used 32020 elements which included the shells used for the impactor and glass. The impactors' element length was 0.25 mm and the glass 1.25 mm. The glass mesh was then refined so that the element size was 0.625 mm and then further refined to 0.3125 mm with 108820 and 416020 elements respectively. The computational power and solution time were also recorded for each mesh size. The results of this study can be found in Chapter 6. The model was then split into a quarter in order to reduce computational power and solve time. The appropriate boundary conditions were then added to the edges of the glass and impactor. The results from the quarter model can also be found in Chapter 6.

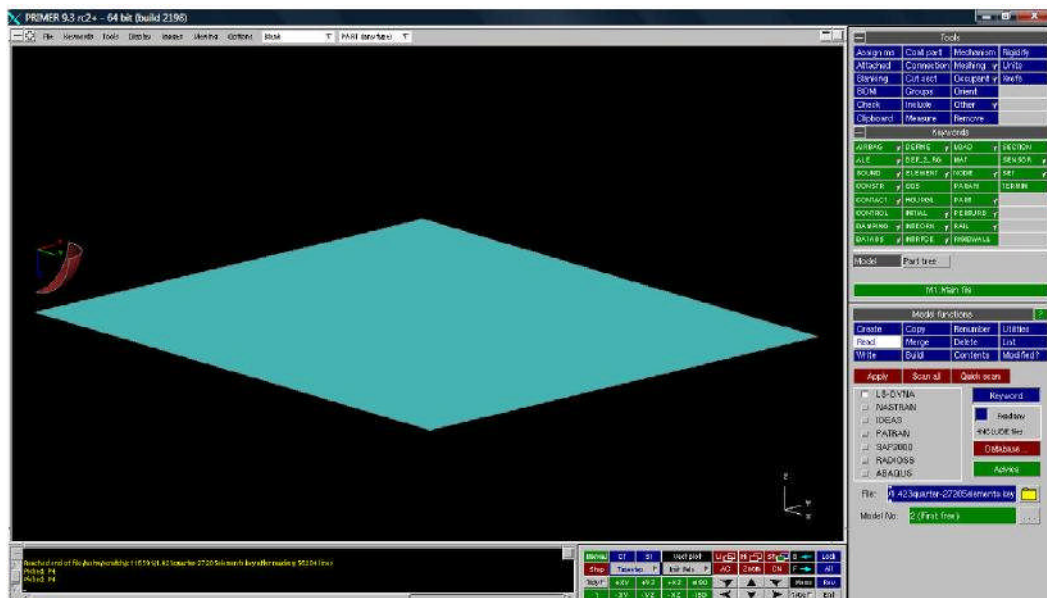


Figure 21. Quartered laminated glass model with impactor.

A sensitivity study was conducted in order to try and determine which material property or materials properties were most sensitive to change. The sensitivity study would be conducted by increasing the original material properties in 10% increments. As it has been reported that glass initially fails before the onset of plastic deformation, the proof stress value was replaced by the tensile strength value taken from Callister (2007). The non-impacted glass ply fails under tension while the impacted glass ply fails in compression. As one strength value was put in place of the proof stress, the sensitivity study will initially increase the tensile strength. The model assumes that both glass plies fail at the same time therefore as the glass initially fails under tension, the compressive strength will not be considered. The results from this study are reported in Chapter 6 and discussed in Chapter 7.

Experimental Methodology

The original testing regime at Cranfield Impact Centre could not be conducted due to an equipment failure which could not be rectified in the available time. A considerable amount of time and effort was spent on this setup, therefore it is included in this report under Section 5.2. No results from the original testing regime are reported in this document as these results were replicated in the second series of tests. The experimental setup and procedure used for the validation of the numerical simulation can be found in Section 5.3.

5.1 Glass Samples

Fifty laminated glass and twenty single ply glass samples were supplied by Independent Glass Company Ltd. The laminated glass samples had a nominal thickness of 6.4 mm with a tolerance of ± 0.2 mm (within 3.125%). The glass samples consisted of two 3 mm glass plies with a 0.4 mm PVB ply sandwiched between the glass. The twenty single ply glass samples had a nominal thickness of $3 \text{ mm} \pm 0.2 \text{ mm}$ (6.67%). All samples were 200 mm^2 and did not have etched edges.

The construction of the laminated glass used in this research can be found in Figure 20 of Chapter 3: Material Characterisation where $a = 200 \text{ mm}$, $b = 200 \text{ mm}$, $h_i = 3.0 \text{ mm}$, $h_p = 0.4 \text{ mm}$ and $h_o = 3.0 \text{ mm}$.

All glass samples were manufactured from annealed float glass and were likely to have been supplied from the same batch; however this could not be guaranteed. It was not possible to define the configuration of each laminated glass sample in terms of which side of the glass (tin-side or air-side) was in contact with the PVB.

As part of the material characterisation process, an attempt was made to determine the tin-side of the glass. As tin impurities in the glass are not visible to the naked eye, an Ultra-Violet light was used in an attempt to determine the construction of the laminated glass. It had been suggested that UV light can detect tin impurities and when shone against glass will give a cloudy white

reflection (Hogg, 2009). However, this method proved unsuccessful and the construction of the glass could not be established. It was recommended that specially developed 'Tin-Side' equipment (TinCheck – Bohle, 2009) should be purchased. However, due to limited time and resources, this was not possible and the glass construction was not determined.

During the project, a further twenty 200 mm² 3 mm annealed float glass samples were ordered so that mechanical testing could be conducted to aid with the material characterisation process. It was intended that the material properties gained from this testing could then be used to give an improved model representation of the behaviour of the glass.

52 Original Testing Regime

The author must clarify that no results are recorded from this testing regime due to the failure of equipment, however the setup details are explained below.

A readily available test rig (drop tower) was modified to suitably measure the deceleration of a projectile during impact. As seen in the Original test rig setup., (Figure 22) the drop tower was clamped to a flat static test bed in order to provide stability on a highly accurate plane.



Figure 22. Original test rig setup.

The drop height of the 2.17 kg impactor was adjusted via a pulley system and string that was clamped to the frame. The plastic tubing helps keep the impactor contained after the first impact has been conducted. The drop height of the impactor can be adjusted to the nearest 5 mm using line of sight and the scale attached to the plastic tubing.



Figure 23. Post test original experimental setup.

A spirit level and angle meter were then used to ensure the steel frames and test rig frame were level. The centre of the lower steel frame was accurately measured so that the impactor would strike the centre of the glass. Small holes

were then drilled in the lower frame and the adjustable base of the test rig - i.e. the area where the 200 mm x 200 mm steel frame was clamped as (shown in Figure 23). Pins were then attached to the lower steel frame so that the test rig was totally constrained in the X and Y planes. Once in place, the lower steel frame was checked again to ensure it was normal to the impact direction. The frame was adjusted by placing small aluminium coupons under the edges that needed to be raised.

Figure 24 shows a sketch of the upper and lower steel frames. Prior to testing the glass samples were placed on the lower steel frame. The upper steel frame was then placed directly on top of the glass and four clamps were placed in the middle of the four sides of the frames.

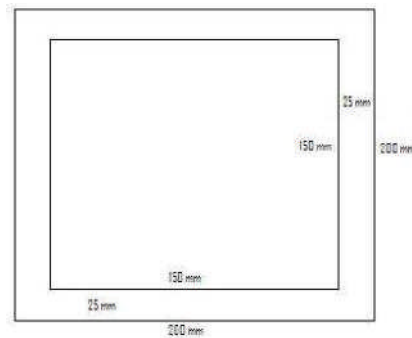


Figure 24. Sketch of the upper and lower frame dimensions. Thickness = 5 mm.

The frames were clamped to the base of the test rig and tightened to a torque of 5 Nm (based on the work by Grant *et al*, 1998).

The impactor was cleaned with soap and acetone and the accelerometer was attached. The accelerometer was wired to an amplifier/signal box which, in turn, was connected to the channel box. The National Instruments channel box (used to define which channel the laptop would read from) was then connected to a laptop via a USB connection. A readily available LabView program was modified to be fit for purpose so that the output of the accelerometer was recorded in g. This program measured a change in voltage from the accelerometer and converted this figure into a change in acceleration measured

in g. The front panel and block diagram for this program can be found in Appendix E.

As seen in Figure 23, bubble wrap was attached tightly around the sides and rear of the test rig to prevent flying glass shards from causing injury to the laboratory's occupants. Before drop tests were conducted, a polystyrene board was placed at the front of the test rig to further ensure the safety to the laboratory's occupants. During testing and handling of glass samples, safety goggles and protective gloves were worn. Prior to testing, a standard operating procedure and health and safety inspections were carried out by the project supervisor. The documentation for these reports can be found in Appendix D.

The instrumentation was tested and calibrated using aluminium honeycomb. Finally, the ambient temperature, atmospheric pressure and humidity were measured and recorded.



Figure 25. Original test setup post failure of single ply annealed float glass.

Once the instrumentation was calibrated testing could begin. The impactor was clamped at a set height then, with the instrumentation triggered, the impactor was released. The instrumentation was then stopped and the results were recorded. After each test, the frames were cleaned of excess broken glass.

During the calibration stage of testing, the accelerometer failed. As no other accelerometer was available, equipment had to be sourced from elsewhere at Cranfield University. A Rosand IFW instrumented falling weight impact tower was available, however the geometry of the FEA model had to be changed in

order to fit the new impactor profile. The test regime that was used for the validation of the numerical simulation can be found in the following section.

5.3. Implemented Experimental Testing

5.3.1 Test Setup and Conditions

The laboratory temperature ranged between 21.5°C and 23°C and the relative humidity measured between 30% - 45%. A Type 5 Rosand Instrumented Falling Weight Impact Tester (version 1.08 – 12 bit) was used to measure the change in acceleration during impact.



Figure 26. Type 5 Rosand Instrumented Falling Weight Impact Tester.

Aluminium coupons were attached to two steel bars in order to prevent the steel frames from moving in the horizontal plane. The correct positioning of the steel bars was then determined to ensure the impact occurred at the centre of the glass. The steel bars were then clamped to the surrounds of the impact tester. The glass was placed between two steel frames (see Figure 24) and clamped to the aforementioned steel bars. The two steel frames were then clamped and tightened to a torque of 5 Nm (Based on the work by Grant *et al*, 1998). Prior to

testing, the impactors mass and dimensions were recorded (mass = 2.66 kg,

diameter= 16 mm).

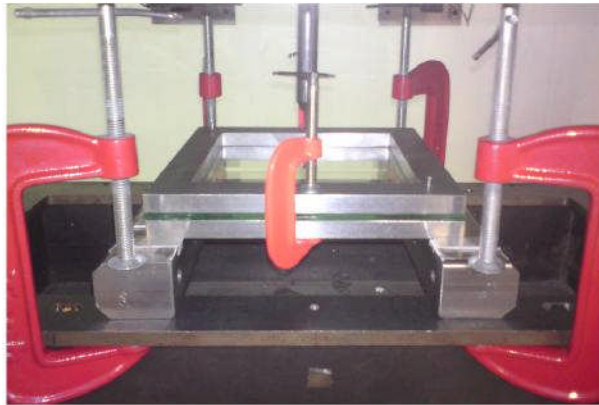


Figure 27. Laminated glass clamped between two steel frames.

The impact tester was calibrated using the 'zero' function on the Rosand IFW software so that the velocity could be adjusted. The velocity was then set using the Rosand IFW software (see section 5.3.2). Using the relationship $v = \sqrt{2gh}$ (v = velocity, g = acceleration due to gravity and h = drop height), the software calculated the drop height. The 'Go To' function then allowed the impactor to be adjusted to the required height. The system was then armed and the hand held trigger release button pressed. A warning was then sounded and the impactor was released. Tests were conducted three times at different velocities. Testing started with an impact velocity of 0.75 m/s and increased in increments of 0.25 m/s to a maximum of 4.00 m/s. The actual velocities usually differed from the predicted velocity; the actual impact velocities are reported in Chapter 6 – Results.

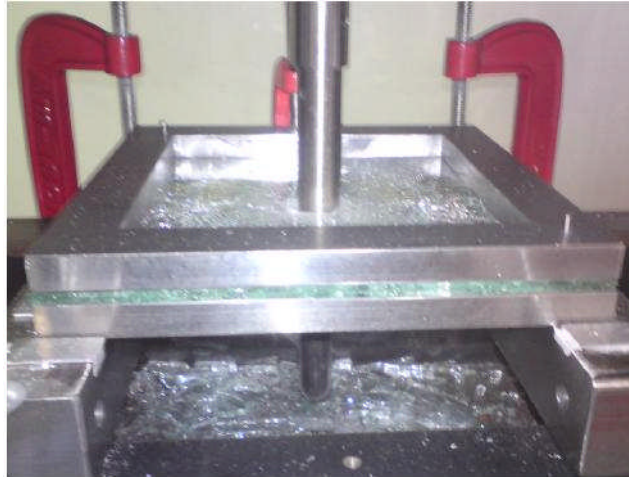


Figure 28. Laminated glass after an impact (velocity = 4 m/s).

The impactor acceleration data was then recorded and saved to the computer. After the data were filed, the impactor was reattached to the drop tower and the clamps were removed. The tested glass was then removed, labelled and stored in a safe place. Finally, the area was cleared of glass shards and a new glass sample was clamped.

High speed filming was conducted at five stages during testing and is discussed further in Section 5.3.4.

5.3.2 Instrumentation

A Kistler load cell, type 9031A, (sensitivity – 4.28 pC/N, range – 6000-60000 N, linearity – 0.5% FSO) was used to measure the acceleration during impact. The acceleration was displayed on a standalone computer using the Rosand IFW (Standard System) software, version 1.11p (1998). Four thousand data points were collected over a time period of 100 ms; one point every 25 ms. A 1000 Hz filter was used to reduce signal noise and filter undesirable frequencies.

5.3.3 Health and Safety

The health and safety implications of the 'Implemented Experimental Testing' were considered to be virtually identical to the previously documented standard operating procedure (SOP) and health and safety report. The Rosand drop

tower proved to be safer than the previous custom made test rig due to the fact a test could not be performed until all doors surrounding the impact area were closed. Furthermore, a warning sound was given off by the drop tower; a hand held device was used to release the impactor and no persons were permitted to be within two meters of the impact. The SOP and health and safety report for the implemented experimental testing can be found in Appendix D.

5.3.4 High Speed Filming

High speed filming was conducted using a Photron FASTCAM 1024PCI video camera with a Nikon 50 mm F1.8 lens (Figure 29). Two 150 Watts InterFit Tungsten 3200 lamps were positioned so that the lighting was maximised around the impact area. With the lighting available, the maximum frame rate and shutter speed were both set at 3000 (333 μ s/frame). The resolution was set to a maximum of 1024 x 256 pixels. The camera's tripod was placed at the best possible angle available and the camera set to focus on the impact area.

The camera had the ability to be triggered via a hand held device; therefore it was possible to trigger both the impactor release and high speed video simultaneously. Photron FASTCAM Viewer (version 3.2, 2006) software was used for the high speed digital imaging. Excess frames were cut from the video in order to minimise hard disk usage. The exported AVI files were then used as a means of validating the numerical prediction fractography.

To ensure good visibility of the glass samples, two clamps were removed.



**Figure 29. Photron FASTCAM 1024PCI high speed video camera and PCI card.
(Taken from Photron, 2009).**

Results

6.1 Experimental Testing

The acceleration data for this research is included in Section 6.3 – validation results. The raw data from the experimental testing can be found electronically on the CD accompanying this document.

6.1.1 High Speed Video

Shown in Figure 30 are frames from the high speed video data collected during the experimental testing.

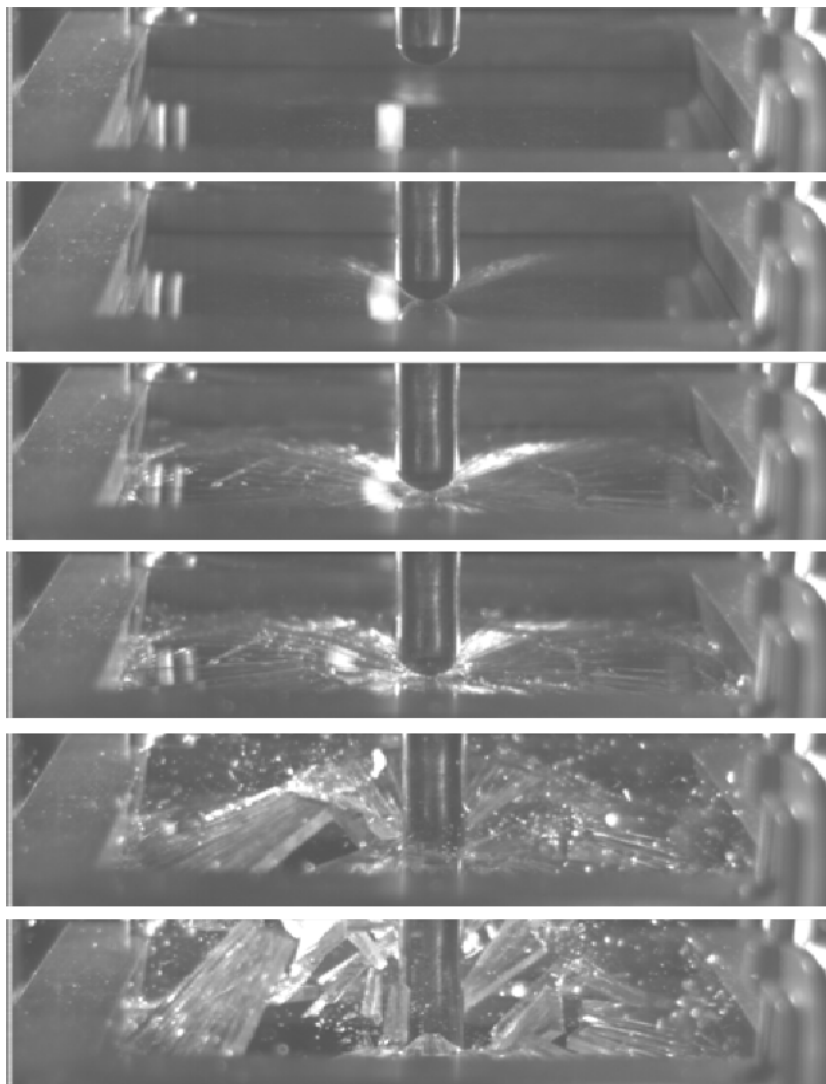


Figure 30. High speed video sequence of an impact to single ply annealed float glass (impact velocity 2.5 m/s).

The images were recorded at 3000 fps (1 frame/333 μ s). The first set of results shows the fracture of single ply annealed float glass as a comparison against the laminated glass results. AVI data collected during this research can be found on the accompanying CD.

The results of Figure 31 show a high speed video sequence of the experimental testing. The laminated glass is impacted at a velocity of 2.5 m/s so that evidence of radial and circumferential cracking can be seen.

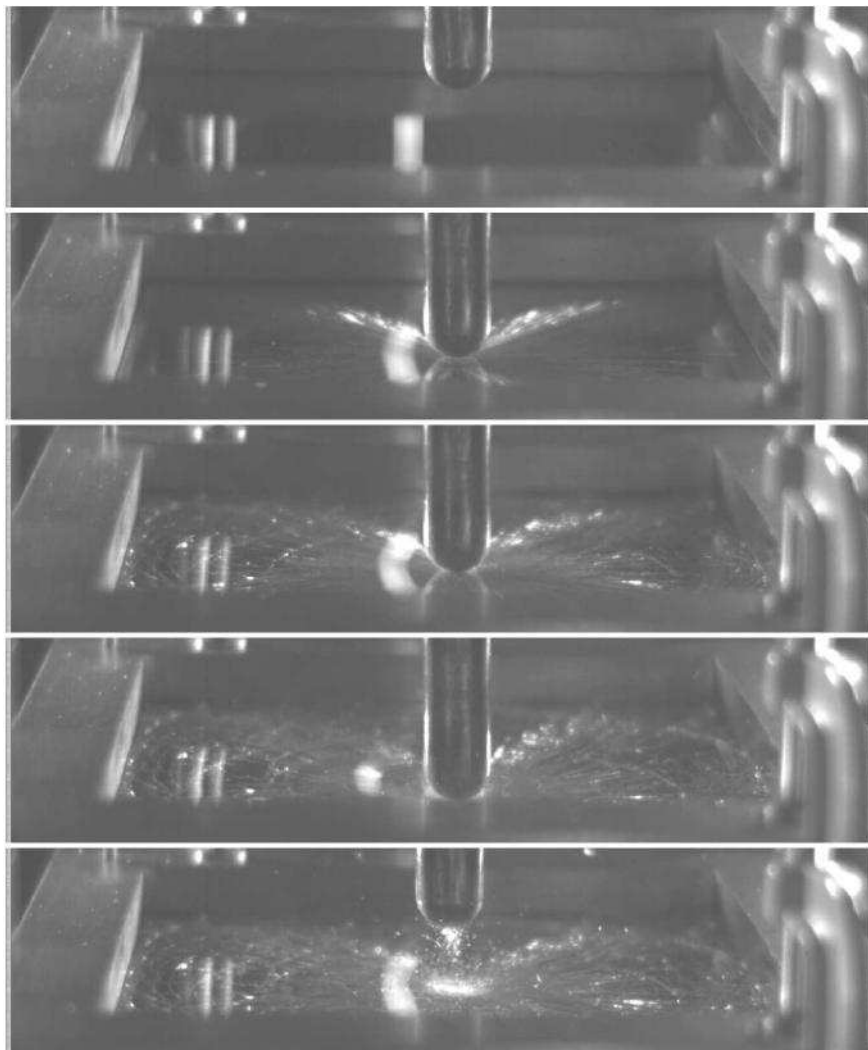


Figure 31. High speed video sequence of an impact to laminated glass (impact velocity 2.5 m/s).

Figure 32 shows laminated glass impacted at 4 m/s where full penetration can be seen.

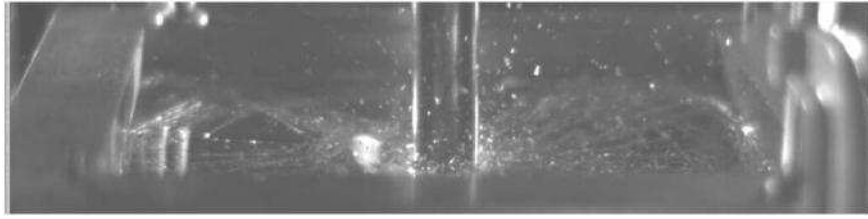


Figure 32. Full penetration of the laminated when subjected to impact at 4 m/s.

6.1.2 Glass Sample Topology

Shown in Figure 33 are photographs of the post impact laminated glass samples. The individual impact velocities for each photograph are reported.

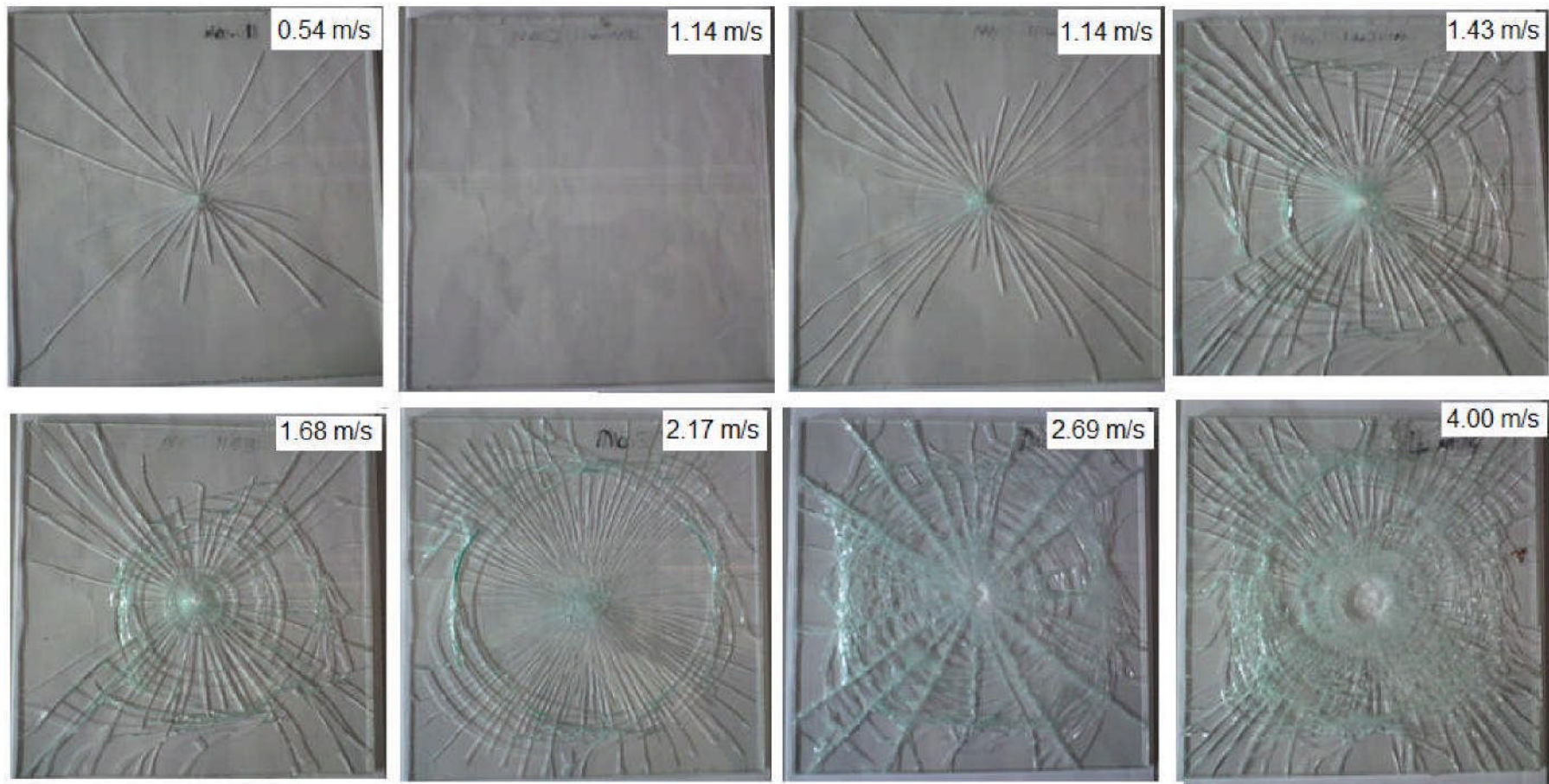


Figure 33. Glass topology results with impact velocities.

6.2 Numerical Simulation

The graphical response taken from D3PLOT for the results found in Section 6.3 is reported below for an impact velocity of 2.17 m/s.

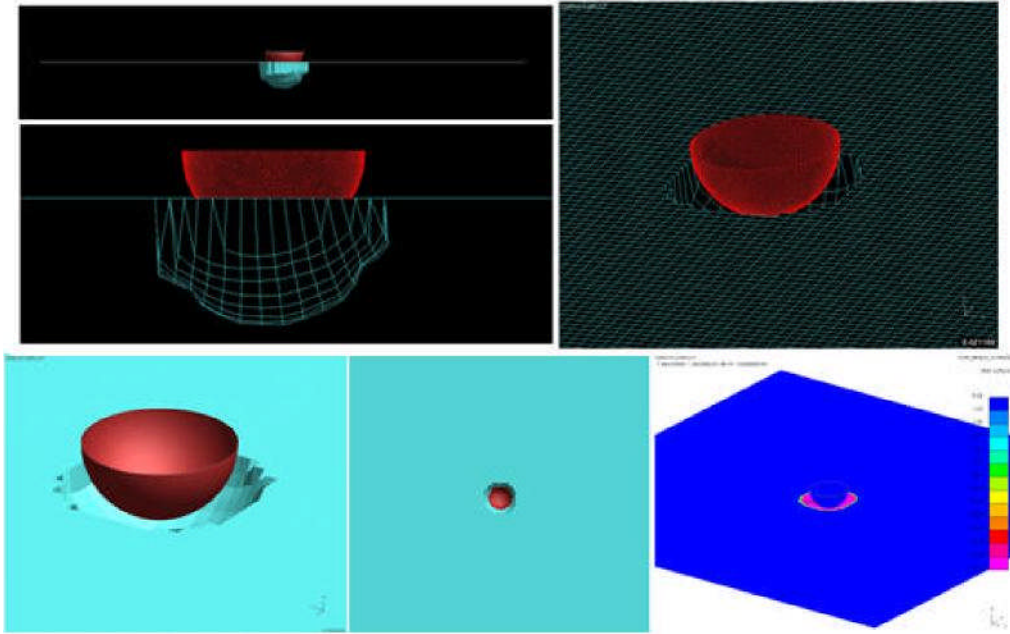


Figure 34. D3PLOT graphical response of an impact at 2.17 m/s.

6.2.1 Convergence

A convergence study was conducted to optimise the model. The performance of each mesh refinement is reported below with the resultant solution time.

The solution times of the models with 32020, 108820 and 416020 elements were three hours, thirteen hours and fifty-four hours respectively.