Soft impact response of laminated glass plates

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Keywords: Soft impact, Laminated glass, Bird strike

ABSTRACT

A laminated glass typically consists of two layers of glass and one layer of polymer. It is utilised in many applications in which the glazing is exposed to external threats like impact or blast. In this paper, damage development of laminated glass plates by soft impact is investigated in both low and high velocity regimes. Low velocity impacts (up to 4 m/s⁻¹) were conducted using a drop tower. Soft impact was achieved by attaching a silicon rubber cylinder to a flat steel impactor, with a diameter larger than that of the rubber, which itself is backed by a 16.9 kg weight. Different velocities were obtained by dropping the weight from various heights. For high velocity impacts (up to 220 m/s⁻¹), a gas gun apparatus was used. The silicon rubber cylinder was fired, using a sabot, in a 25 mm diameter barrel. High speed photography was employed to monitor the deformation and damage development in the laminated glass samples. Laminated glasses with different types of polymer interlayer were tested. The results show a better impact resistance for laminated glass with a stiffer polymer interlayer at both low and high velocity regimes.

1 INTRODUCTION

Laminating glass panels is an effective strategy for improving safety of glass structures against impact. Due to intrinsic brittleness, monolithic glass panels can fail abruptly when subjected to impact with many sharp and small fragments flying at high velocity. This implies a great danger to people around these structures. In laminated glass windows the glass panels are adhered together with a polymer interlayer. The role of this polymer layer is to preserve the structure integrity in the case of failure in glass layers and reduce the risk of flying glass fragments.

Impact on laminated glass windows can be catagorised to hard and soft impact. The term ‘hard impact’ refers to an impact in which the deformation of the projectile is negligible compare to that of the target. In contrast when the strength of the projectile is far less than that of the target and the projectile undergoes extensive deformation during its interaction with the target, the impact is called “soft impact”. The impact can be further sub-divided according to its velocity to low and high velocity. According to Backman and Goldsmith [1], the “low velocity” term is referred to impacts occurred by velocities less than 25 m/s. The impact by large windborne objects on architectural glass windows or pedestrian head impact to car windshields can be classified in this category. In this paper, the term “high velocity” only refers to sub-ordnance velocities (25-500 m/s) [1] as this is a relevant velocity range for bird strike (mostly happens in take-off and landing [2]).

Despite detailed studies on the performance of laminated glass against hard impact, far less attention has been paid toward soft impact response of these structures. Dharani and Yu [3] numerically investigated the impact response of laminated glass windows against impact by large soft projectiles such as collapsed trees or ceiling wood flying during hurricanes. The failure modes and the location of failure initiation were investigated for soft projectile with two nose shapes: hemi-spherical and blunt. It was found that in contrast to hard impact in which the failure is initiated by Hertzian contact stresses, for a large and soft projectile, bending stresses at the opposite surface to the impact
are responsible for the failure. The nose shape of the impactor also determines the failure mode. While for a soft hemi-spherical impactor the failure occurs at the back side of the outer glass layer, for a soft blunt projectile the failure is initiated at the back side of the inner layer. Shetty et al. [4] also numerically investigated the impact response of laminated glass windows for both soft and hard impacts. They concluded that under both cases the thinner outer glass layer results in a better prefigure stress pattern than a thicker one. Also a thicker interlayer generally lowers the stresses in the failure critical areas.

Pacios et al. [5] investigated the soft impact response of monolithic and laminated glass using a 50 kg twin-tire pendulum at the speed up to 4.85 ms\(^{-1}\). The effect of glass type, boundary conditions, thickness and dimensions of the glass plates were studied. The height of impact had been gradually increased until the sample broke. It was found that the loading, e.g. the shape of strain and acceleration traces, is significantly influenced by the boundary condition (e.g. four pin supported compared to two sides supported). Increasing the height of the drop only increases the level of strain and force and the shape of the traces remained the same for one particular boundary condition.

Pedestrian head impact on the car windshield also can be considered as the low velocity soft impact. Normally laminated glass windows are tested against a headform consisting of a hollow aluminum sphere with a rubber [6] or PVC skin [7]. Zhao et al. [8] numerically studied the response of laminated glass against pedestrian head impact. They argued that the thickness of inner glass layer (non-impacted side) is an important design parameter determining the impact resistance of the structure. On the other hand, the thickness of outer glass layer (impacted side) and PVB interlayer has no significant effect on the impact resistance.

Laminated glass windows are also used as a transparent protective shield against high velocity impacts. Bulletproof glass and aircraft windshields are the two examples. Aircraft windshields are subjected to two main impact threats including hailstone and bird. However, the probability of damage by bird strike is higher, as most of the incidents with hail impact can be prevented by the help of modern weather radars. Amongst the total number of bird strikes between 1999 and 2008, 13% of the strikes had been located on the windshield [9]. Although, bird strike was the subject of many studies for nearly 70 years, very limited experimental data has been published. This is partially due to the cost of running these experiments and mostly due to confidentiality of the results. According to FAR/JAR/CS 25.775, the windshield should be able to withstand against an impact by a 4 lb bird at the cruising speed without penetration. At such a high speed, bird is known to behave like fluids during the impact which can be well described by hydrodynamic theory [10]. Different studies were carried out in order to characterise the impact load imposed by bird on different structures including rigid and deformable targets [10–12]. The loading imposed by bird depends on the respond of the target including its material characteristics and target compliance. Laminated glass windshield is a multilayer structure consisting of several layers of polymer and glass (in most of modern aircraft designs it typically consists of five layers). This means that the interaction between the soft projectile and laminated glass is even more complex. Kangas and Plgman [13] investigated the response of various windshields with different materials and types of panel construction against birds with the weight of 0.45 to 7.25 kg impacting at the velocity of 200 ms\(^{-1}\). They suggested that the primary factor affecting the impact performance of the laminated glass windshields is the thickness of plastic interlayer.

In this investigation the aim is to investigate the effect of type of polymer interlayer on the soft impact response of laminated glass. The impact resistance and the failure mode at both low and high velocity are of interest.
2 MATERIAL

The laminated glass specimens used in this study are square plates with dimension of 100 × 100 mm. The plates consist of two layers of chemically toughened glass which were laminated using autoclave at Beijing Institute of Aeronautical Materials (BIAM). The chemically toughened glass plates were manufactured using alumina silicate float glasses which had been initially edge smoothed and then were soaked in potassium salt solution for ion exchange. The glass plates were cleaned before lamination and its tin side was used for the lamination. Three different polymer interlayers are used: Thermoplastic Polyurethane (TPU) - KRYSTALFEX® PE499 from Huntsman, Polyvinyl butyral (PVB) from DuPont and Ionoplast interlayer - SentryGlas® Plus (SGP) from DuPont. The quasi-static uni-axial tensile behaviour of these three polymer interlayer is shown in Fig. 1. At room temperature PVB and TPU are in the rubbery state while the SGP shows more glassy response as its glass transition temperature is 55 °C [14]

![Figure 1: Quasi-static uni-axial tensile response of PVB, TPU and SGP interlayers.](image)

The details of various test specimen configurations can be found in Table 1. Through case 1 to case 3, two layers of chemically toughened glass with the thickness of 2.2 and 4.0 mm are used (the thinner glass layer will be faced the impactor). While changing the polymer type, the thickness of the polymer interlayer is kept similar through case 1 to case 3. Due to limitation in the conventional polymer interlayer thickness available in the market, two layers of polymer were used in lamination for achieving the desired thickness. Case 4 is a 6.0 mm thick monolithic chemically toughened glass. Although the thickness of this monolithic glass plate is not exactly equal to the total thickness of glass layers used for laminated glass specimens (0.2 mm thinner), its impact performance will be used as a guideline for comparison of laminated glass plates (case 1-3).

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Glass and polymer layers</th>
<th>Average plate thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>2.2 mm glass/1.27+1.91mm TPU/4.0 mm glass</td>
<td>9.54 ±0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.23</td>
</tr>
<tr>
<td>Case 2</td>
<td>2.2 mm glass/1.52+1.52mm SGP/4.0 mm glass</td>
<td>9.43 ±0.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.37</td>
</tr>
<tr>
<td>Case 3</td>
<td>2.2 mm glass/1.52+1.52mm PVB/4.0 mm glass</td>
<td>9.35 ±0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.25</td>
</tr>
<tr>
<td>Case 4</td>
<td>6.0 mm monolithic glass</td>
<td>6.0 ±0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.01</td>
</tr>
</tbody>
</table>

Table 1: Different configurations of test specimens used in this study.
3 LOW VELOCITY IMPACT RESPONSE

In this section, the response of laminated glass specimens as well as a 6.0 mm monolithic glass will be assessed under low velocity impacts. This kind of impact regime, heavy mass and low velocity, is more relevant for applications such as architectural glass impacted by a deformable heavy windborne or pedestrian head impact on the car windshield. Nevertheless, the test method and parameters are not aimed to exactly simulate those impact scenarios and a more general understanding on the behavior of laminated glass plates under low velocity soft impact is of interest. However the outcomes still can be transferable to those research areas.

3.1 Experimental set up

Laminated glass specimens with the size of 100×100 mm were clamped to a metallic fixture by using twelve M8 bolts. The clamper has an opening with the size of 70×70 mm. In order to avoid any direct contact between the glass and metallic clamp which can lead to stress concentration at the clamper edge and ultimately glass premature failure, rubber gaskets were used (Fig. 1). To provide a uniform and repeatable pressure in the clamped area which will be consistent for all of the test specimens, a certain level of compression on the rubber gaskets should be applied. This was provided by introducing a metallic spacer with a thickness of 15 mm which its thickness is less than the total thickness of laminated glass with two rubber gaskets (approximately 17.5 mm). Although there is a little variation in the total thickness of the laminated glass as can be seen in Table 1, the effect of this variation believed to be small in total clamping pressure. The bolts were tightened until the clamper come to contact with metallic spacer. This causes the rubber gaskets to be compressed by nearly 30%. A thinner metallic spacer (11.5 mm thick) was used for the monolithic glass to provide the similar amount of pressure. Apparently the amount of pressure at the boundary should be chosen low enough to prevent any damage in the glass layers under clamped area.

![Figure 2: Schematic of clamping arrangement for the test specimen.](image)

Low velocity impacts were conducted using a drop tower machine. Velocities ranging from 0.5 to 3.5 ms⁻¹ were achieved by dropping a mass of 16.9 kg from heights between approximately 100 mm to 550 mm. To produce soft impact, a silicon rubber cylinder with the length of approximately 28 mm were cut from a cord of commercially bought silicon rubber with shore A hardness of 60. The diameter of cylinder was 13.8 mm and cut with two flat parallel surfaces. The rubber cylinder was attached to a flat steel connector with the diameter of 40 mm. The diameter of steel conneector was chosen to be bigger than that of rubber cylinder to keep providing support while the deformable cylinder expands laterally. A piezoelectric sensor (PCB model 224C) was screwed to the other end of steel connecter and was used for measuring the impact force.

In order to observe damage development during the impact two high speed cameras (Phantom Miro-M310) were used. As shown in Fig. 3, one of the cameras was used for monitoring the deformation and damage on top surface of the specimen as well as deformation of the soft cylinder. The other camera was used to observe the back side of the specimen using a flat mirror oriented 45° with the respect to camera. The light was provided by halogen lamp from the top of specimen. To
facilitate the observation of cracks the bottom surface of the specimen was painted with a thin white layer which provides diffuse light in the captured images (Fig. 3).

Figure 3: High speed images showing the deformation of the soft impactor (top row) and damage development in the laminated glass sample (bottom row) subjected to low velocity impact. t=0 is when the impactor first come to contact with the target.

3.2 Test methodology

For measuring the impact critical energy, multiple impacts were conducted on a same specimen. Critical impact energy is defined here as the minimum impact energy required to break the sample (even one of the glass layers in the case of laminated glass). The specimens were impacted by a 16.9 kg weight initially dropped from 100 mm. The height of drop was then gradually increased with 50 mm increments (8.3 J increment in term of impact energy) until the sample breaks. An example can be found in Fig. 4, where a 6.0 mm thick monolithic glass is subjected to multiple soft impacts. As can be seen the height of drop is gradually increased from 100 until 550 mm where the sample finally breaks. From Fig. 3, it is obvious that the soft nose in front of falling weight is gone through extensive deformation during its interaction with sample; also the contact area between the projectile and target increases by nearly 3 times compare to rubber cylinder original diameter. As a result, the nature of the loading and subsequently stresses experienced by the sample are very different from that of hard impact where the Hertzian contact stresses is concentrated over a small area and is one of the major causes of failure [15,16]. Absence of large contact stresses allows impacting a sample several times without affecting its critical impact energy. A separate experiment was conducted confirming that the failure of the sample is not affected by the number of impact tests and the sample only fails when the impact energy reaches its critical value.

Figure 4: Multiple impacts on a 6.0 mm monolithic chemically toughened glass.
3.3 Results and discussion

Low velocity impact tests were performed on the four configurations listed in Table 1. In total four repeat tests were conducted on each configuration. Fig. 5 shows the comparison between the force traces obtained from soft impact of these configurations. In Fig. 5a, all of the samples were subjected to a similar impact, a mass dropped from the height of 300 mm which results an impact with approximate velocity of 2.4 m/s. At this velocity, the impact energy is not sufficient to break any of the samples and the impactor rebounds back. This produces a nearly symmetric force trace which is an indicator of elastic impact. It can be seen that the contact time for all of the configurations is nearly similar, maybe with the exception of case 2, for which the contact time is slightly less than the others. Although the stiffness of the laminated glass with SGP interlayer (case 2) is significantly greater than the other two interlayers [14,17], the difference in the contact time is very small. Hence, it seems that the contact time is not significantly affected by the stiffness of the target for this kind of soft impact (Fig. 5a) and is more controlled by the size and hardness of the deformable impactor, silicon rubber in this case. The peak force however, is greater for the stiffer targets: monolithic glass and case 2.

![Figure 5: Comparison between impact force traces resulting from low velocity soft impact of laminated glass with TPU, PVB and SGP interlayer and a 6.0 mm monolithic glass for (a) same drop height of 300 mm and (b) at the point of breakage.](image)

Fig. 5b show an example of force traces when the impact energy is high enough to break the sample. For the laminated glass specimens both of the glass layers nearly break at the same time, with fracture normally initiated from the backing layer. As can be seen the force nearly drops to zero when the glass layers breaks (around 10 ms). After that the response is mainly governed by deformation of the polymer interlayer. The level of force in this stage is significantly smaller.

The critical impact energy is plotted in Fig. 6 for all cases. The columns show the averaged value of the four repeat tests while the error bars indicate the variation in each case. The laminated glass with SGP interlayer performs the best with critical impact energy higher than that of a 6.0 mm thick monolithic glass. Both of the laminated glass with PVB and TUP interlayers underperform the monolithic glass with the laminated glass with PVB performs slightly better.
In the absence of contact stresses, it seems that the impact performance is mainly determined by the flexural stiffness of the laminated glass which itself depends on the rigidity of the polymer interlayer (Fig. 1) and its ability to transfer shear forces between the two glass layers. Fig. 7 shows the pictures taken from the back side (non-impacted side) of failed plates for different configurations. Failed monolithic glass plate is not shown in Fig. 7 as the sample breaks to very small pieces. For laminated glasses with TPU and PVB (Fig. 7a and c), the failed sample looks very similar, radial and circumferential cracks in both layers while the whole structure is still intact. For these cases only the glass fragments on a small area at the centre of the plate flies off. This is significantly greater for the laminated glass with SGP interlayer (Fig. 7b). Also it can be seen in Fig. 7b that the polymer interlayer is ruptured and the whole plate fractures to four large pieces.

4 HIGH VELOCITY IMPACT RESPONSE

In order to assess the performance of laminated glass windows in conditions similar to what happens in the bird strike, soft projectiles need to be fired at velocities close to take-off, landing velocities. While normally real birds are used in industry to assess the performance of laminated glass windows, gelatin and RTV rubber projectiles have also been employed and show to create pressure profiles close to that of a real bird [18]. The use of these substitute materials has several advantages including better repeatability and more control on orientation, homogeneity and isotropy of the projectile compare to a real bird. In this study RTV rubber projectiles were used and fired using a gas gun apparatus. Two laminated glass configurations with highest and lowest impact breakage energy in section 3.3, the laminated glass with SGP and TPU respectively, are subjected to impact at the velocity of 220 ms\(^{-1}\). The performance and the failure mode under high velocity impact are then compared with that of low velocity.
4.1 Experimental set up

For achieving high velocity impacts, a gas gun apparatus is used. A schematic of the gas gun set up is shown in Fig. 8. Helium gas is used to feed a 4 litre cylinder to pressures up to 10 bar. The projectile is accelerated through a 3 m long barrel by opening a pneumatic valve. The velocity of the projectile is measured by two IR sensor pairs located at the end of the barrel. A series of the calibration tests were performed using a high speed camera aligned with the travel direction of the projectile. A good agreement was observed between the speeds obtained from the two methods. The target is located inside a safety chamber to protect the surrounding from the flying fragments caused by impact. The size of the laminated glass specimens and their clamping condition are exactly the same as described earlier in section 3-1. The side doors are made from thick polycarbonate help observing the impact event as well as illuminating the target.

![Figure 8: Schematic of the gas gun set up used.](image)

As mentioned earlier, RTV rubber (the same rubber used for the low velocity impact) is used for projectile material. The rubber projectile has a cylindrical shape with flat faces at both ends and has the diameter of 13.8 mm and length of 28.0 mm. This gives the aspect ratio (length/diameter) of approximately two. The aspect ratio of the projectile is a crucial parameter which can significantly affect the hydrodynamic loading [10]. In order to fire a soft projectile, a sabot or carrier is needed. The sabot should have sufficient rigidity in order to help the soft projectile accelerating through the barrel and at the same time to protect it from distortion by expanding gas. The sabots here are machined from high density polyethylene (HDPE) with internal and external diameter of 14.0 and 24.8 mm respectively. The projectile and its sabot are shown in Fig. 9a and b. A thin layer of tape was wrapped around the projectile which helps positioning it inside the sabot. The projectile with its sabot was then fired through a 3 mm long barrel with 25.0 mm internal diameter.

The sabot must be stopped at the end of the barrel before the projectile reaches the target, as it can cause unwanted damage to the target. Fig. 9c shows the sabot stopper used for this purpose. This cone-shaped stopper was made from steel and has a 30 degree angle. This angle has been determined through a series of numerical simulations in order to optimise the release of the projectile with the minimum possible disturbance. The cone shape of the stopper helps opening up the sabot and the projectile passes through the central hole of the stopper which has a diameter of 14.0 mm. The deformed shape of the sabot after impact is shown in Fig. 9d.
4.2 Results and discussion

Fig. 10 shows the interaction of a rubber projectile impacting at the velocity of 220 ms$^{-1}$ with a laminated glass target. Since the duration of loading is very short (240 µs), in total 6 images were taken with 40 µs intervals (Fig. 10). As described by [10,18], at these velocities, hydrodynamic theory can well explain the stages of deformation, as can be seen in Fig. 11. As soon as the projectile comes to contact with the target, the material at the contact point is suddenly brought to rest which generates a shock wave propagating at a very high velocity and in a direction opposite to the travel direction of the projectile (stage 1). The pressure inside this shocked area significantly rises which also known as “Hugoniot pressure”. Formation of release waves at the edge of the projectile which propagates inward (stage 2) causes significant drop in the pressure [10]. The duration of this high intensity pressure (Hugoniot pressure) period can be approximated by the time needed for the release waves to reach the centre of the projectile [10] and it depends on the diameter of the projectile as well as the speed of sound in the shocked material [10]. This duration also depends on the curvature of projectile nose and, for example, is smaller for a projectile with a hemi-spherical end compare to a flat end [10]. For a water cylinder with diameter of 10 and 20 mm, the duration of this high intensity pressure is approximately 5 and 10 µs respectively [10].

Figure 10: Interaction of a silicon rubber projectile traveling at the velocity of 220 ms$^{-1}$ with a laminated glass specimen.
In the transient phase (stages 1 and 2), stress waves are also generated inside the target with the magnitude of pressure equal to that inside the shocked area in projectile [10]. By looking closely in the high speed videos in Fig. 10, it can be seen that the frontal layer, which a 2.2 mm chemically toughened glass, is already broken at the second image which is 40 µs after initial contact. This indicates that the stress waves generated during the high pressure phase has enough intensity to fracture the frontal layer.

After several reflection of release wave and by finishing this transient phase, the material steadily moves radially (stage 3) imposing a constant pressure on the sample which is known as “steady state pressure” and has considerably lower intensity than the Hugoniot pressure. The duration of this stage is longer and can be approximated by the time which the projectile needs to travel over its length. However, this approximation gives time which is much higher that the value we observed during the experiment. This can be partly explained by the fact that due to elasticity in the projectile, the projectile does not flow completely as expected in hydrodynamic regimes (as can be seen for the images from t= 160 µs). Another explanation can be slowing down of the projectile during its interaction in the target as similar observation is reported by [21] for gelatin projectile. While the loading is highly transient in the first stage and the time is not sufficient for the target boundaries to be activated, there is enough time in the steady state regime and the whole plate response to the applied loading. By the stage 4, all of the momentum of the projectile is transferred to the target.

Fig. 12 shows the laminated glass with TPU interlayer impacted at the velocity of 220 ms\(^{-1}\)(the same sample shown in Fig. 10). As can be seen only the frontal layer breaks while the back layer is still intact. An extensive damage can be seen on the contact area, at the centre of the plate. As described earlier the damage in the frontal layers occurs in the initial phase where high intensity stress waves were generated. The fact that no damage can be observed in the back layer indicates that the amount of momentum of the projectile, which is mainly transferred in the steady state stage, was not sufficient to break the sample. This failure mechanism observed under high velocity impact, caused by high pressure stress waves, therefore seems to be very different with the one observed under low velocity impacts where the failure is mainly caused by flexural stresses and initiated from the back side of the specimen. The same test was performed on the laminated glass with SGP interlayer. No damage observed in either of the layers. This indicates that despite the difference in failure mechanism in low and high velocity regimes, stiffer interlayer provides a better impact resistance.
Figure 12: Failure pattern of laminated glass with TPU interlayer (case 1) impacted at the velocity of 220 ms\(^{-1}\).

5 CONCLUSIONS

The performance of laminated glass windows consisting of two layers of chemically toughened glass and a polymer interlayer is evaluated under low and high velocity soft impacts. The results show that the type of polymer interlayer significantly affects the performance under both low and high velocity regimes with laminated glass with stiffer polymer interlayer performs the best. However, the type of failure is very different at low velocity compare to that of the high velocity. In low velocity, failure is normally initiated at the back side of inner glass layer (non impacted side) for the laminated glass windows due to development of flexural stresses. In contrast, the failure in initiated in the outer glass layer (impacted side) due to high intensity stress wave in the early stage of contact.

6 ACKNOWLEDGMENT

Much appreciated is the strong support received from Beijing Institute of Aeronautical Materials (BIAM). The research was performed at the AVIC Centre for Materials Characterisation, Processing and Modelling at Imperial College London.

7 REFERENCES


