Asian Review of Mechanical Engineering
ISSN: 2249-6289 (P) Vol.8 No.1, 2019, pp.8-10
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DOI: https://doi.org/10.51983/arme-2019.8.1.2467

Effect of Type of Adhesive Material on the Strength of Bullet-Proof Glass: A Parametric Study

Nitin Thakur[1*], Rabinder Singh Bharj[2] and Pramod Kumar[3]
[1]Ph.D. Research Scholar, [2&3]Associate Professor,
[1,2&3]Department of Mechanical Engineering, NIT Jalandhar, Punjab, India
[*]Corresponding Author
E-Mail: intnitin@gmail.com

***Abstract* -Laminated glass armors play key roles in defense and architecture due to its high aesthetics and inviolability. Armor designing is based upon Wave propagation phenomena produced during a high velocity impact. Laminated glass or bulletproof glass usually comprises of two or more glass sheets bonded by an interfacial layer of adhesives and backed with a high strength ductile polymer (polycarbonate). Typical bonding agents include either high performance adhesives or synthetic resins such as Polyurethane or Polyvinyl butyral (PVB). Recent literature review infers that the ballistic performance of armors is markedly influenced by both the type and thickness of bonding agents, which may be explained by the acoustic impedance mismatch between laminate materials. This paper documents a novel simulation parametric study, considering the material of adhesive layer and thus concluding that, type of adhesive layer plays an important role in maintaining the strength of the bullet-resistant glass. This study took into account the effect of three types of bonding agents (epoxy, polyurethane and PVB) having constant thickness of 1.50 mm, on the ballistic performance of the laminated glass, against AK-47 ammunition projectiles. Simulations were performed in Ansys Explicit Dynamics using a finite element method approach.**

***Keywords:* Bullet-Proof Glass, Adhesives, Ansys, Ak-47**

I. INTRODUCTION

Armors provide protection against penetrating projectiles and fragments from blast waves. Whenever and wherever transparency is must, laminated glass or bulletproof glass are the only alternatives. Thus armored vehicles or structures are always equipped with laminated glass or bulletproof glass to safeguard its dwellers [1]. Basic fabrication of laminated glass consists of a layer of adhesive such as ethylene vinyl acetate (EVA) or Polyvinyl butyral (PVB) sandwiched between multiple layers of glass and this assembly is backed with polycarbonate [2].Normally projectiles are composed of AP ammunitions, therefore a hard strike face is necessary to break up or distort the projectile. Additionally, to obtain portability and comply with ergonomic aspects designing light armors is need of the hour, which explains the increasing interest in the ballistic investigations in search of new materials. When a high-energy AP ammunition projectile impacts a bulletproof glass, the top layer erodes and breaks the projectile; furthermore, the shock waves of the impact, fractures the glass in a conical pattern distributing the residual energy over a much larger area on the backing plate (adhesive/ polycarbonate); therefore, the polycarbonate backing layer acts as a resilient membrane, which deforms to absorb the remaining kinetic energy of the projectile, stopping fragments of glass and the projectile itself [3,4].The impact over laminated glass results in a compressive stress shock wave, which propagate as a tensile wave upon reaching the interface. The impedance mismatch between the glass and the backing material determines the tensile wave amplitude [5,6].However impedance mismatch changes at glass and adhesive material interface and can alter with the thickness of the adhesive [7,8].

There is a scanty literature available to define role of the adhesive layer because, experimentally it is difficult to control the adhesive thickness, and to measure the changes of stress waves inside the layer [7, 8, 9]. Nonetheless, today finite element analysis (FEM) modeling enables us to understand the physics of ballistic events. Although, there are new methods available in FEM analysis, likewise smoothed-particle hydrodynamics (SPH) which is a mesh free approach, sometimes gives unrealistic results especially in high velocity impact events [10]. Therefore, Lagrangian meshed approach was used, which do have limitation of excessive distortions of elements, but it can be overcome by using erosion control [11].This novel parametric study analyzes the effect of three types of bonding agents (epoxy, polyurethane and polyvinyl butyral (PVB)) on the strength of bullet proof glass, to ascertain its impenetrability against AK47 projectiles.

II. MATERIALS AND COMPUTATIONAL MODELS

To carry out the simulations in the current study the materials used are layers of Soda-lime glass, Polyurethane (PU), Polyvinyl butyral (PVB) & epoxy, backed by Polycarbonate. Three different numerical models were created using Ansys Explicit Dynamics as per dimensions given in Table 1 below. Sample 143 had the interfacial layer of polyurethane, similarly Sample 243 and Sample 343 had the interfacial layers of PVB and Epoxy respectively. Each sample was having dimensions of 500 mm x 500 mm x 43 mm. Each sample was numerically impacted at its centre with AK-47 projectile, having a velocity of 720 m/s. For ceramics the most simple and widely applicable numerical model is the Johnson-Holmquist model (JH-2) [12], which was used for the simulations of soda lime glass and its material properties were acquired from the reference [12]. Similarly properties of PVB, PU, Epoxy and polycarbonate were taken from the references [11, 13, 14, 15] respectively. Simulations were performed in Ansys Explicit dynamics, using a finite element (FEM) approach. AK47 rifle projectiles were numerically modeled employing Johnson-Cook material parameters with the velocity of 720 m/sec which were assumed to be made of Armor Steel [16]. Hexahedral elements were used for meshing with a size of 1mm x1mm x 0.5mm. This relevant size was evolved after convergence study; further decreasing the size of the elements was not making any noticeable difference in the simulations, but was significantly increasing the computational time. Projectile was modeled with element size of 0.009 mm. To eliminate the problem of excessive distortion of elements, erosion control had been used.

TABLE I THICKNESS OF EACH LAYER FOR THE SAMPLES

Samples	Thickness (mm)					Number of bonding inter layers				
	Glass	PVB	PU	Epoxy	PC	glass	PVB	PU	Epoxy	PC
Sample143	11	------	1.50	------	5	3	------	3	------	1
Sample243	11	1.50	------	------	5	3	3	------	------	1
Sample343	11	------	------	1.50	5	3	------	------	3	1

III. RESULTS AND DISCUSSION

In order to bring our study to visualization and to realize, what is the effect of different adhesive layers on the strength of laminated glass, DOP and velocity profiles were compared for each sample.

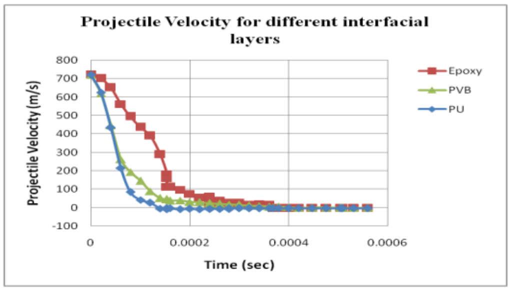

Fig.1 Velocity profile for the projectiles for three Samples 143, 243 and 343

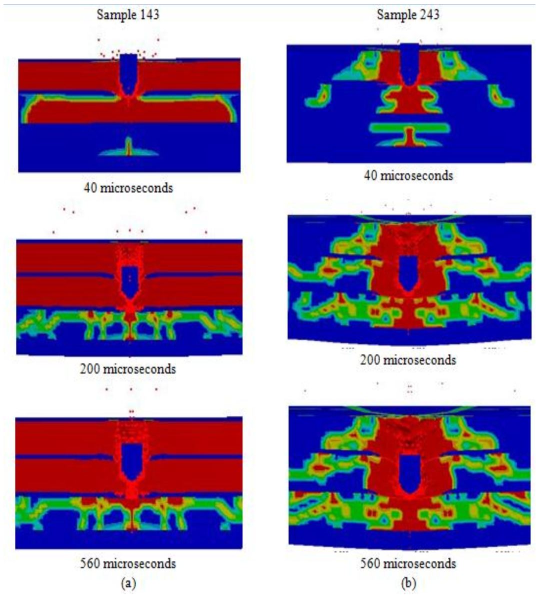

Fig. 2 Depth of Penetration contour plots for Samples (a) Sample 143 and (b) Sample 243

Fig.1 shows the velocity variations of the projectiles for three samples having three different adhesive layers. From this profile it is clear that when we use Polyurethane as the interfacial layer (Sample143) the velocity of the projectile decreases instantly (becomes zero at 150 microseconds), but for the Sample243 and Sample343 the velocity decreases not instantly but gradually.

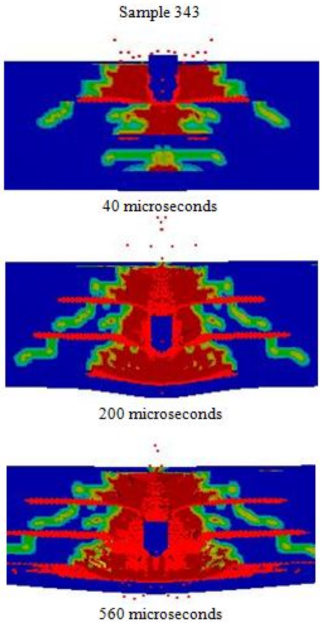

Fig. 3 Depth of Penetration contour plots for Sample 343

Fig.2 and Fig.3 shows the Depth of Penetration contour plots for Samples 143, Samples 243 and Sample 343. From these plots it is clear that the final DOP for Sample 143, Sample 243 and Sample 343, after 560 microseconds is nearly 50 %, 55 % and 70 % respectively and for sample having Epoxy as the interfacial layer, the projectile is even able to penetrate the second layer of adhesive. This means that the sample with Epoxy inter-bonding layer shows the worst behavior in reference to the strength of laminated glass. This behavior is also replicated by the velocity profile, which shows that the sample with polyurethane as the interfacial layer prevents the projectile from penetrating the target within a minimum period of time, as the velocity eventually becomes zero. The reason for this behavior can be attributed to the fact that the Polyurethane adhesive has the better adhesive strength as compared to PVB and Epoxy in concern to the soda-lime glass material and also its elongation at failure is 270-800 % which is better as compared to PVB and Epoxy adhesive [17]. Its excellent adhesive strength distributes, three beneficial attributes to bullet-resistant glass: first, the interfacial layer exposes the ballistic impact shock waves to the much larger area across the laminated glass, thus increasing the shock resistance of the laminates and not confining it to the centre of the laminated glass, secondly the inter-bonding layer binds the resulting splinters so that it adds to the strength of the laminated glass; third the laminated glass undergoes plastic deformation during high velocity impact and thus absorbing energy and reducing perforation by the impacting projectiles.

IV. CONCLUSION

In the current study the effect of three types of inter-bonding layers (PU, PVB, Epoxy) on the strength of laminated glass and on the velocity of the AK-47 projectile is being analyzed. In order to achieve the current prospective the numerical simulations were done in Ansys Explicit dynamics by taking into account the three aforementioned interfacial layers in three different samples. From this study it is concluded that the sample with PU inter-bonding layer shows the minimum DOP of the projectile (nearly 50%) for this configuration of the laminated glass whereas the laminated glass with Epoxy adhesive shows the worst behavior as the projectile is able to penetrate even the second layer of the adhesive. This study shows that the bullet-resistant glass with PU and PVB inter-bonding layer reflects the comparable strength to defeat the threats as compared to Epoxy adhesive.

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