International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 24 (2017) pp. 14514-14522

Perforation of Polycarbonate Sheet When Subjected to Impact Test – A Review

Hasan Muhamad Abid[1*], Qassim H. Shah[2] and Mohd Sultan Ibrahim[3***]**

[1]*Automotive Engineering Section, University Kuala Lumpur, Malaysia France Institute, Section 14, Jalan Teras Jernang, 43650 Bandar Baru Bangi, Selangor, Malaysia.*

[2,3] *Department of Mechanical Engineering, Faculty of Engineering, International Islamic University Malaysia, Jalan Gombak, 50728 Kuala Lumpur, Malaysia.*

Abstract

Polycarbonate (PC) material has a variety of applications which offers high resistance to impact loadings. Perforation performance of a projectile striking a PC target is the main character that determines the resistance capability of PC material. There are three methods to investigate the PC penetration trajectories such as experimental test, numerical modeling and combination of experimental and simulation values. The objective of this review paper is to discuss all the available research methods on the penetration of PC material, and record their potential and lack areas. Moreover investigations of multilayered plates with different materials bonded together with PC plates to observe the impact effects of different projectiles shapes are been discussed. Furthermore the analysis of PC material behaviors during different stress-strain rates are also been presented in this paper.

Keywords: Polycarbonate; Perforation; Impact; stress-strain rates.

INTRODUCTION

Polycarbonate (PC) is an important polymer which has a variety of technical applications such as optical lenses, automotive parts and mainly used as protective shield and safety devices. PC material is transparent, light weight, and has good strength to resist high and low impact velocities. Therefore PC is selected in the design of transparent armors. The high strain yield character improved the impact resistance in PC material [1]. The penetration and damage by a projectile impact analysis is very important to improve the design structure of PC material. Experimental results of PC penetration by ballistic impact resulted in cracking cone, elastic dishing for thin plates, plugging with deep penetration failures occurred in thicker plates [2].

Multilayered plates composed of PC and polymethylmethacrylate PMMA were tested to determine energy absorption and strain-rates [4, 5]. The result showed that for PC-PMMA plates the material displacement increased with the impact velocity increment as reported by Gunnarsson et al. [8, 9]. A PC plate with dimensions of 100mm x 100mm x 3mm used to resist high speed impact of spherical-end projectile. The results of kinetic energy presented the proportional relation between the perforation and impact velocity, and also the clamping types affected the energy absorption performance during the impact [7]. The impact resistance of many sandwich structures was incorporated PC materials backing due its high strain rates have been reported experimentally by many researchers [4, 5, 10, 12, 13, 15, and 20]. In all cases, the performance of projectile penetration is significantly influenced by the projectile shapes [3, 38], impact velocities [4,5], and thickness of PC targets [7]. PC materials exhibited softening and hardening strain effects during dynamic loading as reported Sarva et al. [49]. The stress wave propagation and plate deflection of PC during the impact affects the energy absorption capability [44].

There are many commercial software of finite element code which allows user to model the impact resistance between projectiles and targets, which can validate their results with experimental values. Such the explicit LSDYNA has been greatly used to simulate the impact analysis for many research works [21, 24-26, 31, 34, 39, 40 and 46], and demonstrated significant ability to predict the results of stress-strain rates and energy absorption of PC targets as reported by Mullaoglu et al. [24]. Moreover ABAQUS explicit software is also good in performing the numerical analysis of projectile impact against PC plate and compared well with experimental results [32, 33, 37, 38, 41-43, and 49]. There are other explicit software can model the three-dimensional impact scenario such as ANSYS [28], AUTODYNA [35, 36] and DYNA-3D [45] which produced reasonable results as compared to experimental values.

All the numerical simulation results must be validated by experimental results in order to accurately predict the effect of the impact between projectiles and PC plates such the penetration depth [37], impact velocity and energy absorption capability [41].

The aim of this paper is to review all available methods for PC penetration analysis. The significant method in this analysis is using the experimental tests and numerical simulation, which are been reported. A short review on mechanics of PC material behavior during high and low strain rates loading are been presented.

EXPERIMENTAL TEST

The experiment of polycarbonate plate penetration by ballistic impact of spherical missile was conducted by Wright et al. [1, 2]. The study used three types of thickness plates 2mm, 5mm, and 12mm. All of the plates were in circular shape. The experiment identified five types of fracture deformations as cracking cone, deep penetration, elastic dishing, plugging, and petaling. The spherical missile impact resulted different deformations for different thickness of polycarbonate plates. For the thin plate the failure was in the modes of elastic dishing and cracking cone. Plugging and deep penetration failure modes resulted in the impact test of the thick plate. The petalling failure mode developed in the both thickness of plates subjected to impact by spherical missile. The results also showed the pressure on the projectile nose was similar to the required pressure for expansion of small cylindrical void to the penetrator diameter which was also reasonable.

Normal impact test experiments of different projectile shapes used to study penetration depth of polycarbonate plates. The research focused on the effectiveness of projectile nose profile, penetration resistance of target to projectile velocity. The velocities of the projectiles ranges from 600 m/s to 900 m/s and the thickness of the polycarbonate plates varied from 300mm to 500mm. During penetration, the resisting pressure results showed the average pressure of 290Mpa for flat and ogive nose projectiles and 270Mpa for hemispherical nose projectile. The results were supported with numerical analysis research of penetration depth of polycarbonate targets [3].

A ballistic impact test was conducted on multi-layer thin plates of polycarbonate PC and polymethylmethacrylate PMMA and a set of PC laminates with PMMA-glass intermediate. The result obtained in form of material parameters such as high strain-rate penetration, impact velocity limitation and energy absorption capability. The prediction of semi empirical approach of impact test was obtained and verified. For PC/PMMA arrangement the penetration energy obtained was to scatter as a result of small drop in the projectile velocity. PMMA/PC layout resulted in less energy absorption due to increment in the impact velocity. Thickness increment of PMMA could increase the impact resistance of the composite. The composite of PC-PMMA-PC plate offered considerable amount of visibility at the end of projectile impact which was critical application for transparent armor. Therefore the all plastic laminates composite plates were selected especially in the design applications of transparent armors for vehicles [4, 5].

The experiment of depth-of-penetration (DOP) of transparent armor has been conducted by Bless [6]. The tests focused on the comparison of armor materials. Materials such as soda lime glass, borosilicate glass, spinel, and glass ceramic which were bonded to polycarbonate backing. A spherical-end and sharp projectiles were used in the experiment. The result showed that the spinel type offered the best performance among others. The multi-layered spinel-glass efficiency of was dependent on the spinel thickness and the laminates efficiency did not affected by thickness of bond layer relatively. The sharp projectiles resulted in compressive strength as the important property of the material during the impact, and the spherical-end projectile showed the density affected the penetration resistance of the material. Furthermore the result provided an optimal design of the transparent armor for DOP experiment which also used to evaluate the damage effect ranged from single crack to multi cracks by multiple impacts. Furthermore the difference of material properties associated with polycarbonate backing for the construction of transparent armor affected the perforation capabilities of the projectiles, which also was extremely dependent on the layers different types and their degree of interaction [7].

Goto et al. [8] tested a polycarbonate shield against a fired bullet, the shield was proposed as a protective vest that could defend a person from a fired bullet as the material offers high toughness and transparency added with light weight characteristic. Polycarbonate (PC) plates of 100mm x 100mm with thickness varied from 3mm to 12mm were impacted by blunt projectiles fired by air gun at speed of 212 – 366 m/s. The velocity limit for each thickness of PC plates was tested, and the result was concluded that the relation between the velocity and penetration was proportional. The kinetic energy was necessary for the bullet penetration varied in the board thickness. The types of plate holders significantly affected the impact energy absorption capability during the test. The results of energy absorption of polycarbonate plates in the experiment varied from 26J up to 60J at the maximum projectile velocity.

Transparent protection armors used Polycarbonate (PC) and Polymethylmethacrylate (PMMA) materials for their high impact resistance and lightweight characteristics. For better impact resistance PC and PMMA were bonded to form composite plates with varying thickness and layouts [9, 10]. In the experiment blunt projectiles were used to impact the plates. The study examined the material deformation and effectiveness of the PC-PMMA composite plates to resist the projectile impact and energy absorption capabilities. The result showed for a given thickness, the displacement of the material increased proportionally with the impact velocity for all plate types. During the impact PMMA plates had less deformation compared to PC at certain impact velocities. The composite plates of PC-PMMA experiment aimed to develop non-perforating tests on different types of layers, moreover after the experiments PC plates had more ductile failure and PC-PMMA composite plates showed brittle failure as reported by Gunnarsson et al. [11, 12].

The composite of Polycarbonate (PC) and Multi Walled Carbon Nanotubes (MWCNTs) plates test against high velocity impact using an Instrument falling Weight Impact Tester was conducted by Allafi et al. [13]. The experiment studied the impact energy and strength, and fracture toughness. The plates' size of 100mm x 100mm and 1mm thickness was compressed by 20 tons load at temperature of 280°C. The dropping projectile weighted about 10 kg and dropped at 0.5m height at 3.12 m/s velocity. A thin plate of MWCNT bonded to PC improved the impact resistance which increased impact energy absorption. The result showed l MWCNT material had high yield strain and kinetic energy absorption behavior when compared to PC matrix material. However, the enhancement by MWCNTs was limited for PC due to the effects of material thermal softening at high strain rate impact. The microstructure changes after the test showed that as the strain rate increased more decrease occurred in the density of PC-MWCNTs composite compared to a pure PC specimen. This was due to high energy dissipation in PC-MWCNTs which formed cracks during the impact.

Anderson et al. [14] conducted the experiment of ballistic impact on a composite of Borosilicate glass and Polycarbonate plates for transparent armor design. The projectile was special designed steel bullet. The composite plates constructed by 15mm-thick borosilicate glass and 9.25mm-thick polycarbonate materials. The study used high imaging recorder to analyze the penetration rate and damage on the target. The observation concluded that speed of cracks was not depended on the impact velocity. The maximum impact velocity varied from 0.8 mm/μs to 1.2 mm/μs. The impact damage was proportional to the speed of impact. Moreover the crack speeds found during the experiment were verified and compared with others work and resulted with significant agreement.

Composites of Carbon Fiber Reinforced Plastics (CFRP) with Polycarbonate were examined by Tanaka et al. [15]. The applications of the composite had improved the automotive industry due its light weight attributes. PC improved the impact resistance of the matrix of Carbon Fiber Reinforced thermoplastics (CFRTP). The results were compared between CF-PC and CF-PA to determine a better composite structure for impact resistance, and the effect of molecular weight was examined. A drop weight projectile of 2kg was used in the experiment to strike the composite plates. The specimens of 2mm-thick of CF-PC and CF/PA were molded for 600s at 300°C and 270°C respectively. The experiment results provided the CF-PC was lighter compared to CF-PA but better in term of impact resistance as incorporated with PC. Also molecular-weight of PC had little effect on the impact resistance of CF-PC plates.

Multi-layered composite plates of glass and polycarbonate (PC) were used as packages of ballistic glass. The PC sheets used in the experiment were in form of new and used ones from the same manufacturer. The projectile was a 0.44 Magnum caliber that fired at distance of 5m from the target plates. The objective of the experiment was to determine the recycling possibility of broken PC sheets for protection purposes. The mechanical properties of PC were not affected by the impact for both used and new sheets, however after the test the recovered plates showed severe damages and cannot be recycles and used again. The dynamic mechanical test on the damaged PC sheets, after completely being delaminated from the ballistic package, revealed high residual stresses. Moreover removing PC sheets methods from the package did not affect the glass absorption capability, and also avoided the reuse of the sheets in the ballistic package [16].

Experiments of compression test for polycarbonate (PC) were performed using Split-Hopkinson pressure bar [17–19]. The research focused on the mechanical response in form of low and high stress strain rates. Also the data used to setup Johnson-Cook parameters and pre-heated specimens were used in the experiment to evaluate the effect of thermal softening [18]. The observation on PC reported high strain rates increment depended on the material yield strength. The results showed hardening enhancement affected rate sensitivity of material response, and the increase of pre-heating temperature led into decrease of yield stress. Figure 1 presented the stress-strain rates results of Split-Hopkinson-Pressure-Bar (SHPB) compression test for PC.

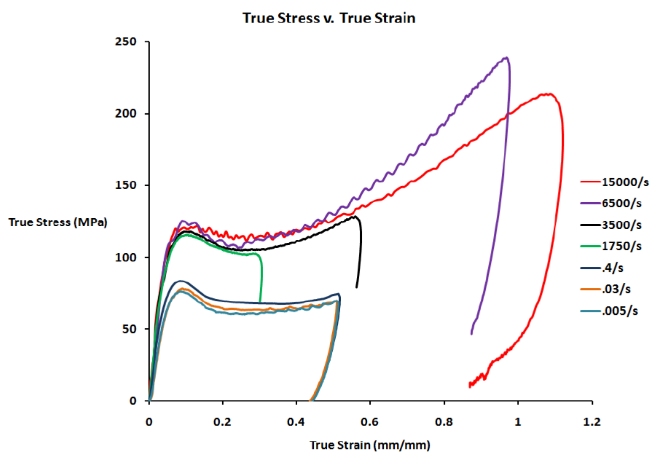

Figure 1: Representative of Stress-Strain curves from SHPB compression test of polycarbonate [18].

Moreover the results of stress strain rates at range of 0.0001/s to 4600/s were presented in Figure 2, which demonstrated the initial linear section of the curve increased as strain rates increased. Furthermore PC specimen under compression loading resulted in nonlinear deformation behavior that exhibited softening of the material [19].

The experiment of high strain rate behaviors of polycarbonate (PC) material based on low strain rates values was conducted by Kendall et.al [20]. The research aimed to study the difference in mechanical properties of PC and polymethylmthacrylate (PMMA) materials at high strain rate loading. Two testing types were used in the experiments, first as the Quasai-Static experiment up to 0.1/s at low temperature. The second test type was High-Rate experiments for more than 1000/s rates. The results showed PMMA stress was too high which formed strain softening during the high strain rates. PC material had the opposite effect that occurred in PMMA, only small temperature rise could be able to simulate high strain rate behavior for PC material. The research recommended for further work to investigate the microstructure effect of PC and PMMA material at high strain rates [20].

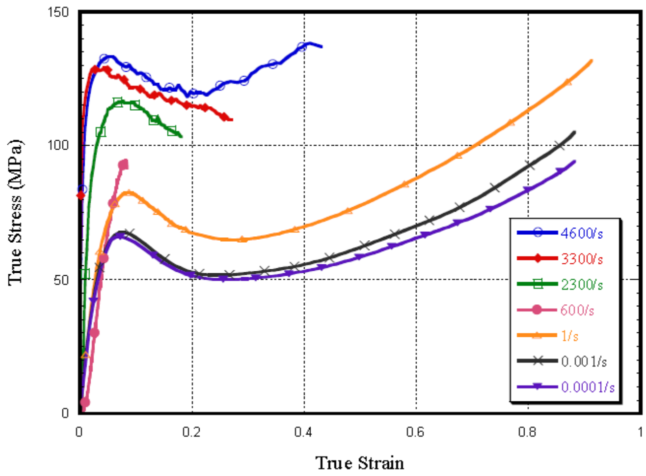

Figure 2: Stress-Strain rates of polycarbonate [19].

NUMERICAL ANALYSIS

Nandlal et al. [21] examined the ballistic impact of a wide range of projectile types that struck on polycarbonate (PC) plates. Finite Element Software known as LSDYNA was used to perform the numerical analysis. Five types of different projectiles were used to strike the PC targets, three steel spherical projectiles and two Fragment-Simulated-Projectiles (FSPs). The study aimed to predict impact limits of PC plate 6.35mm thick against the different types of projectiles. The results of the numerical analysis showed that the ballistic impact performance was significantly affected by geometry and mass of the projectiles. The spherical projectiles had less penetration into the target compared to FSPs of the same mass. The plug formation and bowl-shaped effects at the high strain section were found to be larger by FSPs than spherical projectiles.

Finite element method used to simulate impact tests of a blunt projectile on curved and flat polycarbonate (PC) plates. The numerical analysis focused on the penetration performance based on the ratio of curvature radius and thickness of the plates, which could assist in the design of transparent screen shields for aircraft and automobiles. Two types of curvature were used, negative curve in which the center toward the projectile and positive was in the opposite direction. The simulation results were validated by an experimental work of a flat PC plate perforation with low speed impact. The numerical results concluded that negative curvature plates reduced the penetration capability of the projectiles while positive ones improved the penetration performance mainly for thin PC plates. During early deformations stage, elastic hinge occurred around the center area of the impact for positive curvature thin plates. There was no hinge developed at the impact region for flat, thick positive curvature and negative curvature plates. The effective stress developed around the impact area was high for flat plates compared with positively curved PC panels. Holes were formed due to deletion of destroyed element during the impact, and frictional force did not affect the interface between projectile and plate as reported by Antoine et al. [22, 23].

The investigation of polycarbonate (PC) material performance against impact resistance was conducted by Mullaoglu et al. [24]. LS-DYNA software was used to perform the numerical analysis in this research and PC plate was modeled elastic plastic material. PC plates of 2mm thick and 400mm x 400mm size were modeled to resist the strike of steel spherical projectiles. The assessment was carried out on location at the center of plates, 90mm and 180mm away from the center point, to compare all of the energy absorption capability, von-Mises stress, and plastic of PC plate. The validation of the numerical analysis was achieved by comparing with the literature of an experiment and simulation conducted for flat PC plates against metal spherical projectiles which resulted in good agreement. The observation presented high stress occurred at region of the fixing constrain which developed high plastic strain for all cases. This was because of the limited deflection of the plate due to rigid constraining. It was also noted that large deformation exhibited at the point of impact, and at the fixing region may had penetration effect due to high stress and strain. The highest energy absorption values were found at 180mm for all impact speeds, and also there was no perforation at all impact points with different speeds. Deep dent near to the edge was developed as a result of local material deformation that absorbed projectile energy.

LSDYNA explicit commercial finite element code was used in the analysis of different projectiles impact against composite and sandwiched plates with polycarbonate (PC) material backing to improve the safety of the and reliability of the structure. Different types of materials and nose-shape projectiles were used in the analysis, as well as different projectile speeds were applied in the simulation. The numerical results produced by the solver were compared with experimental results of the same parameter that validated the ability of the simulation prediction. The observation reported the relation between the projectile velocity and impact force was proportional, but the impact period between the projectile and plate was dependent on the composite stiffness which was less for curved plates. The energy absorption capability results used to enhance the presented design [25, 26].

Sport protective gears were designed by multilayered composite materials to resist the impact of flying objects such as cricket balls. Finite element method modeled the impact scenario as numerical analysis. The study examined the protective composite strength against the ball impact. Evthylene-Vinyl-Acetate (EVA) foam was used in the composite due its good ability in energy absorption, and polycarbonate (PC) layer used to resist against the perforation during the impact, also the human tissues were modeled as a layer in the sandwich plate [27]. The cricket ball was modeled by viscoelastic material, and the simulation conducted variable speeds and angles of the impacting ball against the targets. The numerical results were validated by experimental data and provided good agreement. The impact speeds of the ball varied up to 45m/s, for a given velocity the optimization of layers thickness was found to be good for 4-8-3mm arrangement PC-EVA-PC respectively which offered minimum force transfer to the human skin. The contact force on the skin increased linearly as the impact velocity increased. The research aimed to assist in further investigation for new materials that could reduce fatal injuries in cricket games [27].

Polycarbonate (PC) was used as a lightweight transparent protective material in a wide range of application including military protective equipment. Protective eye wears against bullet were made of PC material that could resist Explosive Ordnance Disposal [28, 29]. Moreover a protective wall was designed using PC material to withstand blast of 15psi / 103.4kPa pressure, and also lower cost and high impact resistance compared to glass. The system was modeled using ANSYS software, and shock wave results were verified and compared with measured values during the experiment. The numerical results demonstrated that PC wall was naturally elastic and could resist blast pressure of 103.4kPa several times. Long cracks developed during the final test in the center of PC plate, also small crack occurred from the previous testing. The cracks did not propagated more during the followed tests. In all cases of testing, the wall resisted the blast nine times and the maximum pressure was 176.023kPa. The research recommended furthering investigating the analysis by changing the blast duration [28].

LSDYNA explicit software of finite element analysis used to model the simulation of impacting polycarbonate (PC) specimens [30, 31]. The study focused on the processing-induced inhomogeneity of yield stress in PC material. An elastic-plastic strain rate-dependent model was used to model the PC material behavior. The inhomogeneity occurred due to initial higher temperature point or region than the rest of specimen [31]. Different thermal types were introduced in the analysis of notched Izod impact test. The results of fracture energies were compared between the numerical analysis and previous experimental values which provided well agreement. The simulation analysis observation provided that as the mold temperature increased the fracture energy increased proportionally. Therefore higher mold temperature resulted in more impact energy was absorbed by plastically fractured and deformed PC specimen as reported by Xu [30]. PC material had strain softening which followed by strain hardening due to initial high temperature region [31].

Safari et al. [32, 33] analyzed the strain deformation of polycarbonate (PC) at higher strain rates more than 100/s. the research aimed to study the effect of yield and material viscoelastic behaviors of PC material during high strain rates. The constitutive model of PC specimen was constructed by the commercial finite element code known as ABAQUS software. The provided experimental results of dynamic mechanical thermal analysis validated the numerical analysis results which presented good coinciding. The results showed the yield stress increased as the strain rates increased, and the relation between thermal softening and strain hardening affected the after yielding behavior for strain rates more than 8200/s. Furthermore, the validation demonstrated the ability of simulating PC material behavior at very high strain rates up to 10,020/s. the observation concluded that the changes of material constants occured due to the temperature increased during high strain rates.

A composite plate of polymthelmethacrylate (PMMA) and polycarbonate (PC) was used to investigate the penetration of projectile impact. The study analyzed the crack propagation, energy absorption, stress, and impact velocity. The two polymers were bonded by an adhesive, and the projectile had spherical-end shape. The simulation model was done using the explicit finite element code of LSDYNA [34], and also AUTODYNA software used to model nonlinear impact analysis between the projectile and multilayered PC-PMMA palte [34], then the model was compared with previous experimental values and had good agreement. The results showed the crack length and plate deflection were affected by the Young's Moduli and Poisson's Ratio of both materials, including the shear modulus of the bonding between the two plates. PMMA thickness in the sandwich plate affected the crack length too, and PC thickness variation influenced the energy absorption during the impact due to the effect of PC plastic softening and deformation [34, 35].

AUTODYN explicit finite element software was used by Jo et al. [36] to model the numerical simulation of inclined projectiles impacting polycarbonate (PC) targets plate. The study investigated the effect of inclination angles on the projectiles penetration depth and kinetic energy. The projectile velocity was more than 200 m/s and the thickness of PC plate was 7.62 mm. The numerical results was compared with others experimental results and coincided similar pattern of after impact effect. The observation showed that inclination angles between 0° to 20° formed ricochet phenomenon. For inclination angles above 30° the projectiles penetrated the target due to the fracture of tensile and ductility of the material. The relation between penetration velocity and residual velocity was proportional and increased with higher impact velocity.

EXPERIMENTAL AND SIMULATION ANALYSIS

The experiment and simulation of a long projectile impacting thick polycarbonate plates was conducted by Dorogoy et al.

[37]. The study investigated the depth of penetration on PC plates. The 7.62mm long projectile had an Ogive-head shape and struck at the targets at speed range of 151-271 m/s. The targets plates were confined and unconfined types. The numerical analysis of the impact was modeled using the commercial finite element software ABAQUS. The results of the experiments coincided well with the simulation model. The results showed the penetration depth of the projectile depended on the failure strain of PC material which demonstrated high resistance to impact force. Confined plates had small penetration depth due to negative triaxiality that reduced ductility during impact while brittle fracture reduced because of hydrostatic pressure.

Husain et al. [38] modeled different nose shaped projectiles striking thin polycarbonate (PC) plates. The research focused on the energy absorption, residual velocity, deformation mechanism, and ballistic limitation. The projectile geometries of truncated conical and blunt shapes were fired at speed of 106m/s on circular 2.66mm thick PC target. The numerical analysis results were produced by the explicit finite element code known as ABAQUS, and then compared with experimental results that demonstrated good agreement. The observation showed that the impact of blunt projectile had more ballistic limit compared to the truncated conical one. Moreover blunt projectile produced more energy absorption and velocity drop during the impact when compared to the other projectile. After the impact, the two types of projectiles left the plug part attached to the target plate for low velocity impacts. However in high velocity impact the plug separated from the plate which caused velocity drop for both projectiles, also the velocity drop increased as the impact velocity increased rapidly.

The analysis of thin polycarbonate (PC) plate resistance against spherical projectile impact was conducted by Shah et al. [39, 40]. The study investigated the plastic deformation of thin PC plates when subjected to multiple impacts of spherical projectiles that varied in locations and distance of the impact. The impact velocity was considered as low speed of 138m/s and PC plates were shaped into rectangular and circular geometries. Multiple impact locations were used as well as different impact distance between plates and projectiles were applied in the research to study their effects on perforation performance. The numerical analysis of the impact was modeled in the commercial finite element code of LSDYNA. The comparison between the experimental and numerical results coincided good agreement. The observation showed the early material failure occurred at the clamped edge instead of the center point of impact, and the material failure also caused perforation of the plate. The significant difference of plastic failure was due to high constrained plate at the edge of the clamp. The results could be significantly used to enhance the safety of PC transparent armor plates.

A 6.35mm thick Polycarbonate (PC) plates were used to resist the impact of spherical-end steel projectile with 5.46 mm in diameter. The analysis focused on the perforation energy absorption capability during the impact of the polymer that offered lightweight characteristic. The projectiles were fired using gas-gun which formed projectile velocity ranged from 300 to 550 m/s. The numerical analysis model was done by the explicit finite element code known as ABAQUS that provided information about stress, energy and deformation area during the impact. Bothe of the results from the experiments and simulation provided good agreement. The results showed new hierarchical material design improved the distribution of stress and deformation during the impact which enhanced the energy absorption capability of PC plates with no weight increment. The matrix structure offered ductility behavior that limited the deformation at the impact region, which maintained the integrity of the structure during and after the impact. The research recommended modeling a multilayered plate of different material for better energy absorption as reported by Sarva et al. [41].

The penetration depth of a projectile struck a polycarbonate (PC) plate was investigated by experimental test and numerical analysis [42]. A sharp-end projectile with 7.62mm diameter was used in the analysis and 250 x 80 mm^2 PC target with 50 mm in thickness. The commercial software ABAQUS used to model the impact simulation scenarios. The numerical results were verified against experimental values which presented well prediction pattern. The observation demonstrated the projectile penetrated the targets at inclination angles above 30° that was due to the tensile that influenced the projectile direction and penetration depth. The main contributor for PC deformation was the ductile failure coupled with evolution of damage. The deceleration of penetration was a linear function of penetration velocity and it decelerated more with higher impact velocities. The combination effect resulted from tensile and ductile failures influenced the penetration performance into PC plates which was similarly existed in thick polymthelmethacrylate (PMMA) plates as reported by Dorogoy et al. [43]. The ductile failure directed a straight penetration path at the start, and the tensile failure controlled the plate deflection and phenomenon of ricochet.

Hu et al. [44] conducted the experiment and simulation modeling of spherical projectile struck a composite plate of a thin glass plate and a thin polycarbonate (PC) plate constrained by a frame without any adhesive bonding. The research focused on the damage pattern developed in the glass plate with different impact velocities ranged from 61 m/s to 200 m/s. the results of fracture patterns were used to compare both of the experimental and numerical values which seemed to be similar in pattern. The observation showed that in both types of results, rebounding of the projectile occurred and it increased with the increase of impact speed. The numerical results provided the explanation of the complex damage pattern of the glass layer, which occurred due to impact wave propagation and plate deflection. The results concluded the factors determined the brittle fracture pattern were stress wave and impact energy. The boundary conditions could influence the propagation of the stress wave which controlled the crack path.

The effect of tumbling of steel blunt-end projectiles on thin steel and polycarbonate plates was investigated by experiments and numerical analysis. The aim of the study was to analyze the material deformation and failure during the impact. DYNA-3D software was used to model the impact between tumbling and plates, the comparison between experimental and simulation results presented reasonable agreement. The observation showed impact angle influenced velocity drop and trajectory proportionally. Impact angle above 50° stabilized the impact effects on the target plates, which was desirable in armor design for high protection against penetration of a projectile [45].

An experimental and numerical simulation of high strain rate tensile loading of polycarbonate (PC) was conducted by Xu et al. [46]. The research focused on the mechanical response of PC to present comprehensive understanding of PC behavior under high strain rate. A split Hopkinson tension bar (SHTB) was used in the tensile testing at rates ranged from 0.0005/s to 4500/s, which was grouped into two types, quasai-static for low strain rates and dynamic test for high rates. LSDYNA explicit finite element code was used in the simulation to model high rate tensile test of PC. The comparison between the results of experiment and simulation model demonstrated good agreement as shown in Figure 3, both of the results had similar trend path. The results showed nonlinear deformation behavior at different strain rates that included softening and hardening strain of the material. PC material was sensitive to strain rate which influenced the yield stress values proportionally.

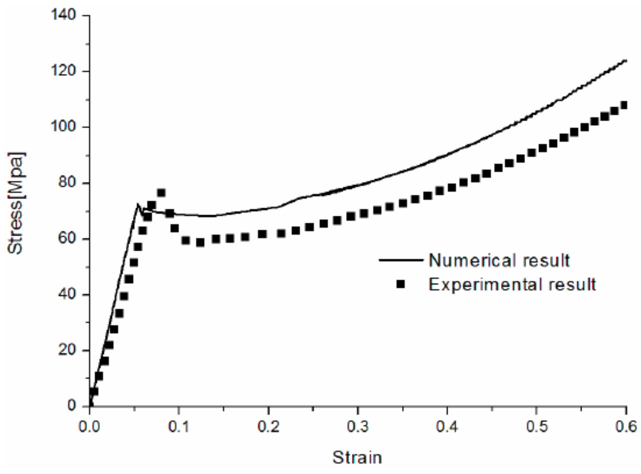

Figure 3: Experimental and numerical results of stress-strain response of PC at strain rate of 0.01/s [46].

Moreover SHTB test of PC was modeled using ABAQUS explicit software by Sarva et al. [47] and Mulliken et al. [48]. The analysis was to study the PC behavior under high tensile loading and the results comparison between the two types of analysis coincided well. In all reports [46–48] concluded the necking mode of PC specimen occurred during high tensile loading that influenced by the stress-strain behavior of PC material.

Sarva et al. [49] conducted high rate loading compression tests for polycarbonate (PC) material by both methods of experiment and numerical analysis. This information aimed to optimize the design of impact resistance applications such as transparent armor safety eye-wears and protective shield. The study investigated PC material behavior under high strain rate compression test using Taylor impact method, which used to investigate plastic deformation behavior of materials under high-rate dynamic loading. The experiment included high speed photography to observe the inhomogeneous deformation progress of PC specimen and to compare the images with simulation model. Explicit finite element code known as ABAQUS used to model the Taylor compression impact test. The final deformed shapes of PC specimens were compared experimentally and numerically which found to be similar in pattern demonstrating the predicting ability during extreme high velocity impact situation. The observation presented PC behaviors of deformation such as softening and hardening strains of the material during the events of dynamic loading. In both test types all PC specimen showed remarkable shortening effect after compression loading.

Forde et al. [50] conducted the experiment of reverse ballistic impacts in order to determine the high and low strain rate of mechanical properties of the materials. The target plates were made of metals such as aluminum, tungsten and mild steel. The projectiles material selected in the test were Cooper, Dural and RHA steel. Also different types of projectiles end-nose were tested in the experiment. Stress gauge data were compared to VISAR results which could produce more detailed outputs for low stress rate level and have response when the load released. The results of the experiment and the simulation (Armstrong-Zeerilli model) were compared. The wave structure that propagated in the projectile rod results showed good agreement between the experiment and numerical analysis which complement well to each other. Furthermore the results under-predict the perforation which was due to mechanisms failure included in the test. In the oblique plate test it was necessary to include fracture to have better simulation results.

CONCLUSION

The article highlighted the available methods of analysis for PC penetration. The three main methods are experiment tests, numerical analysis and combined experimental and simulation results. Simulation results been compared against experimental results to have better modeling analysis. The perforation of PC material was affected by projectile shapes, impact velocities, and thickness of PC targets. Most of the results focused on projectiles penetration performance and energy absorption capability which proved the high resistivity of PC materials. Impact wave propagation and plate deflection of PC during the impact affected the penetration performance.

Moreover the observation showed PC material behaviors during impact exhibited softening and hardening strains for dynamic loading. Furthermore, the numerical model of the impact analysis needs more refinement, such as detailed material type, in order to have better prediction of the event.

REFERENCES

[1] S. C. Wright, N. A. Fleck, and W. J. Stronge, "Ballistic impact of polycarbonate-An experimental investigation," *Int. J. Impact Eng.*, vol. 13, no. 1, pp. 1–20, 1993.

[2] S. C. Wright, Y. Huang, and N. A. Fleck, "Deep penetration of polycarbonate by a cylindrical punch," *Mechanics of Materials*, vol. 13, no. 4. pp. 277–284, 1992.

[3] M. P. M. Hagalil and A. Engineering, "An Experimental Investigation of Deep Penetration into Polycarbonate Targets," *27TH Int. Symp. Ballist. Freibg.*, pp. 1241–1251, 2013.

[4] H. Kasano, "Ballistic Impact Performance of Composite Plate with and without Bonding," *18th Int. Conf. Compos. Mater.*, pp. 2–6, 2011.

[5] A. J. Hsieh, D. Deschepper, P. Moy, P. G. Dehmer, and J. W. Song, "The Effects of PMMA on Ballistic Impact Performance of Hybrid Hard / Ductile All-Plastic- and Glass-Plastic-Based Composites," 2004.

[6] S. Bless, "Using Depth-of-Penetration Tests to Design Transparent Armor," *Exp. Mech.*, vol. 53, no. 1, pp. 47–51, 2013.

[7] M. Grujicic, W. C. Bell, and B. Pandurangan, "Design and material selection guidelines and strategies for transparent armor systems," *Mater. Des.*, vol. 34, pp. 808–819, 2012.

[8] K. Goto, Y. Ohbuchi, and H. Sakamoto, "Development and Evaluation of Protect-board in High Speed Collision," in *The 14th IFToMM World Congress*, 2015.

[9] H. Kim, E.-C. Kang, J.-S. Jang, and J. Suhr, "Spherically shaped micron-size particle-reinforced PMMA and PC composites for improving energy absorption capability," *Composites*, vol. 7978, p. 79780U–79780U–9, 2011.

[10] C. A. Gunnarsson and P. Moy, "Measurement of Transient Full-Field, Out-of-Plane Back Surface Displacements of Polycarbonate during Impact," in *Proceedings of the XIth International Congress and Exposition*, 2008.

[11] C. A. Gunnarsson, T. Weerasooriya, and P. Moy, "Impact Response of PC/PMMA Composites," *Strain*, vol. 1, pp. 229–236, 2011.

[12] C. A. Gunnarsson and P. Moy, "Deformation and Failure of Polycarbonate during Impact as a Function of Thickness," in *SEM Annual Conference*, 2009.

[13] W. Al-Lafi, J. Jin, and M. Song, "Mechanical response of polycarbonate nanocomposites to high velocity impact," *Eur. Polym. J.*, vol. 85, pp. 354–362, 2016.

[14] C. E. Anderson, R. P. Bigger, and C. E. Weiss, "Measurement of damage velocities in impacts of transparent armor," *J. Phys. Conf. Ser. 500 112003*, vol. 500, no. 112003, pp. 1–5, 2014.

[15] K. Tanaka, H. Koriyama, S. Isshiki, T. Katayama, and M. Shinohara, "Effect of the molecular weight of polycarbonate on the impact resistance of continuous carbon fiber reinforced polycarbonate composites," *High Perform. Optim. Des. Struct. Mater.*, vol. 137, pp. 283–289, 2014.

[16] D. P. Reis and J. R. M. d'Almeida, "Evaluation of recycling of polycarbonate sheets used in ballistic glass packages," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 38, no. 4, pp. 1261–1268, 2016.

[17] C. R. Siviour, S. M. Walley, W. G. Proud, and J. E. Field, "The high strain rate compressive behaviour of polycarbonate and polyvinylidene difluoride," *Polymer (Guildf).*, vol. 46, no. 26, pp. 12546–12555, 2005.

[18] A. Dwivedi, J. Bradley, and D. Casem, "Mechanical Response of Polycarbonate with Strength Model Fits," 2012.

[19] P. Moy and T. Weerasooriya, "Strain rate response of a polycarbonate under uniaxial compression," 2003.

[20] M. J. Kendall and C. R. Siviour, "Experimentally simulating high-rate behaviour: rate and temperature effects in polycarbonate and PMMA.," *Philos. Trans. A. Math. Phys. Eng. Sci.*, vol. 372, p. 20130202, 2014.

[21] D. Nandlall and J. Chrysler, "A Numerical Analysis of The Ballistic Perforation of A 6.35-mm Transparent Polycarbonate Plate," 1998.

[22] G. O. Antoine and R. C. Batra, "Effect of Curvature on Penetration Resistance of Polycarbonate Panels," *J. Appl. Mech. Trans. ASME*, vol. 83, no. 12, pp. 1–12, 2016.

[23] G. O. Antoine and R. C. Batra, "Low Velocity Impact of Flat and Doubly Curved Polycarbonate Panels," *J. Appl. Mech.*, vol. 82, no. 4, p. 41003, 2015.

[24] F. Mullaoğlu, F. Usta, H. S. Türkmen, Z. Kazancı, D. Balkan, and E. Akay, "Deformation Behavior of the Polycarbonate Plates Subjected to Impact Loading," *Procedia Eng.*, vol. 167, pp. 143–150, 2016.

[25] A. N. Palazotto, E. J. Herup, and L. N. B. Gummadi, "Finite element analysis of low velocity impact on composite laminates," *Int. J. Sci. Res.*, vol. 1, no. 8, pp. 1205–1209, 1999.

[26] K. R. Ramakrishnan and S. Gu, "Development of a Finite Element Model for the study of the impact behaviour of sandwich panels," in *21th Congres Francais de Mecanique Bordeaux*, 2013, no. Mat 58, pp. 3–4.

[27] S. Sridharan, J. S. Raoa, and S. N. Omkarb, "Finite Element Analysis of cricket ball impact on Polycarbonate-EVA sandwich," *Procedia Eng.*, vol. 112, pp. 28–33, 2015.

[28] K. A. Perry and R. A. Meyr, "Explosion Testing of a Polycarbonate Safe Haven Wall," *Arch. Min. Sci.*, vol. 61, no. 4, pp. 809–821, 2016.

[29] P. M. Kelly, "Lighwieght Transparent Armour Systems for Combat Eyewear," in *19th International Symposium of Ballistics*, 2001, no. May, pp. 7–11.

[30] Y. Xu, H. Lu, T. Gao, and W. Zhang, "Processing-Induced Inhomogeneity of Yield Stress in Polycarbonate Product and Its Influence on the Impact Behavior," *Polymers (Basel).*, vol. 8, no. 3, p. 72, 2016.

[31] A. G. Varghese and R. C. Batra, "Strain localization in polycarbonates deformed at high strain rates," *J. Polym. Eng.*, vol. 31, no. 6–7, pp. 495–519, 2011.

[32] Keivan H. Safari, J. Zamani, F. J. Ferreira, and R. M. Guedes, "Constitutive Modeling of Polycarbonate During High Strain Rate Deformation," *Polym. Eng. Sci.*, vol. 47, pp. 21–25, 2007.

[33] K. H. Safari, J. Zamani, R. M. Guedes, and F. J. Ferreira, "The effect of heat developed during high strain rate deformation on the constitutive modeling of amorphous polymers," *Mech. Time-Dependent Mater.*, vol. 20, no. 1, pp. 45–64, 2016.

[34] G. O. Antoine and R. C. Batra, "Sensitivity analysis of low-velocity impact response of laminated plates," *Int. J. Impact Eng.*, vol. 78, pp. 64–80, 2015.

[35] C. G. Fountzoulas, B. A. Cheeseman, P. G. Dehmer, and J. M. Sands, "A Computational Study of Laminated Transparent Armor Impacted by FSP," 2007.

[36] J.-H. JO and Y.-S. LEE, "A Study of Ricochet Phenomenon for Inclined Impact of Projectile," *Int. J. Mod. Phys. Conf. Ser.*, vol. 6, pp. 443–448, 2012.

[37] A. Dorogoy and D. Rittel, "Effect of confinement on thick polycarbonate plates impacted by long and AP projectiles," *Int. J. Impact Eng.*, vol. 76, pp. 38–48, 2015.

[38] Afsar Husain, Raisuddin Ansari, and A. H. Khan, "Experimental and Numerical Investigation of Perforation of Thin Polycarbonate Plate by Projectiles of dDifferent Nose Shape," *Lat. Am. J. Solid Struct.*, pp. 357–372, 2016.

[39] Q. H. Shah, "Impact resistance of a rectangular polycarbonate armor plate subjected to single and multiple impacts," *Int. J. Impact Eng.*, vol. 36, no. 9, pp. 1128–1135, 2009.

[40] Q. H. Shah and Y. A. Abakr, "Effect of distance from the support on the penetration mechanism of clamped circular polycarbonate armor plates," *Int. J. Impact Eng.*, vol. 35, no. 11, pp. 1244–1250, 2008.

[41] S. Sarva, A. D. Mulliken, and M. C. Boyce, "Mechanics Of Transparent Polymeric Material Assemblies Under Projectile Impact: Simulations And Experiments," in *Proceedings for the Army Science Conference (24th)*, 2006, p. 27.

[42] A. Dorogoy, D. Rittel, and A. Brill, "Experimentation and modeling of inclined ballistic impact in thick polycarbonate plates," *Int. J. Impact Eng.*, vol. 38, no. 10, pp. 804–814, 2011.

[43] A. Dorogoy, D. Rittel, and A. Brill, "A study of inclined impact in polymethylmethacrylate plates," *Int. J. Impact Eng.*, vol. 37, no. 3, pp. 285–294, 2010.

[44] W. Hu, Y. Wang, J. Yu, C. F. Yen, and F. Bobaru, "Impact damage on a thin glass plate with a thin polycarbonate backing," *Int. J. Impact Eng.*, vol. 62, pp. 152–165, 2013.

[45] K. Li and W. Goldsmith, "Perforacion of Steel and Polycarbonate plates by tumbling projectiles," *Int. J. Impact Eng.*, vol. 34, no. 35–36, pp. 4581–4596, 1997.

[46] Y. Xu, T. Gao, J. Wang, and W. Zhang, "Experimentation and modeling of the tension behavior of polycarbonate at high strain rates," *Polymers (Basel).*, vol. 8, no. 3, 2016.

[47] S. Sarva and M. Boyce, "Mechanics of polycarbonate during high-rate tension," *J. Mech. Mater. Struct.*, vol. 2, no. December, pp. 1853–1880, 2007.

[48] A. D. Mulliken and M. C. Boyce, "Mechanics of the rate-dependent elastic-plastic deformation of glassy polymers from low to high strain rates," *Int. J. Solids Struct.*, vol. 43, no. 5, pp. 1331–1356, 2006.

[49] S. Sarva, A. D. Mulliken, and M. C. Boyce, "Mechanics of Taylor impact testing of polycarbonate," *Int. J. Solids Struct.*, vol. 44, no. 7–8, pp. 2381–2400, 2007.

[50] L.C. Forde, W. G. Proud, S. M. Walle, P. D. Church, and R. Cornish, "Reverse Ballistic Impact Stusdies of Thin Plate Perforation," *Eng. Trans.*, pp. 7–8, 2011.