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Effect of distance from the support on the penetration mechanism of clamped circular polycarbonate armor plates

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Abstract

A 1.91-mm thick circular polycarbonate plate of 115 mm diameter was impacted by a spherical steel projectile of 6.98 mm diameter at its center. Subsequent impacts were made at 10, 20, 30, 40, and 50 mm radii of the plate. Dent dimensions for the damaged plate were measured using optical microscope. For a constant projectile velocity of $138\,\mathrm{m\,s^{-1}}$ which was below the perforation limit of the plate under investigation, a maximum thickness reduction close to the edge support was observed. The experimental work was modeled into explicit finite-element analysis program LSDYNA for simulations. LSDYNA was able to predict the dent depth and reduction in plate thickness at impact points precisely. In this research, the effect of the impact location distance from the supports on the damage mechanism of circular polycarbonate armor plates is investigated. The target plate was subjected to constant velocity projectile impacts starting at the plate midpoint and varying the impact distance from midpoint towards the clamped edge. Failure of plate is predicted close to the constrained boundary under uniform conditions.

Keywords: Polycarbonate; Impact; Armor plate; LSDYNA; Thickness reduction

1. Introduction

Due to its good impact resistance properties, the polycarbonate material is used in helmets [1] and bullet-proof armored vehicles. Ploycarbonate (PC) is also under investigation for the development and manufacture of sandwiched panels for bullet-proof vests and armored systems where alternate layers of polymethylemethacrylate acrylic (PMMA) and polycarbonate are used to mitigate the damage caused by high-velocity projectiles [2,3]. Due to their light weight, economical, and easy manufacturing processes, the usage of polymers is on the rise in various industries. Experimental studies reported on the behavior of polymers are not as numerous as on metals and numerical studies are even rare because of the unavailability of appropriate material models [4–10].

The response of rectangular plates subjected to blast loading was reported by [11,12] where the authors explored the response of quadrangular stiffened steel plates. The effects of localized and uniform blast loading on various stiffener locations were studied. It was found that if the stiffeners were located at a localized blast loading position, the deformation of the target plate was minimized but it resulted in tearing failure of the plate near the stiffener edges. The effects of large and close range explosions on circular armor plates have been reported very recently where the scaling of the dynamic response has been studied [13]. Numerical studies on the response of armor systems made up of PC and PMMA were reported [5] where smooth particle hydrodynamics was used to simulate the response of PC and PMMA layers and it has been found that many existing material models can reproduce close range results at the initial stage of simulations. Further numerical results based upon the experiments [14] have been reported in [15] where the effect of varying support

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configurations have been investigated on the plastic failure of the circular steel plates. Circular plates subjected to dense fragment cluster impact [16,17] investigate the failure process of armor plates subjected to a fragment cluster consisting of many projectiles impacting the plate simultaneously. Test results indicate that the impulse and the rate of energy deposition on the target and the impacting duration of the fragment cluster are the most important factors. Considering the above-mentioned works by various researchers, it was deemed important to study the failure mechanism of armor plates subjected to projectile impact at various distances from the plate midpoint.

2. Experiments and results

The material properties available for polycarbonate material at high strain rate found in the literature were very scarce and material models in most cases were incomplete or lacked precision [18–20]. Polycarbonate tensile tests were therefore performed on the test coupon shown in Fig. 1. Stress–strain curve obtained from the tension test at various strain rates is shown in Fig. 2. Failure strain was found to be 150%. The yield strength

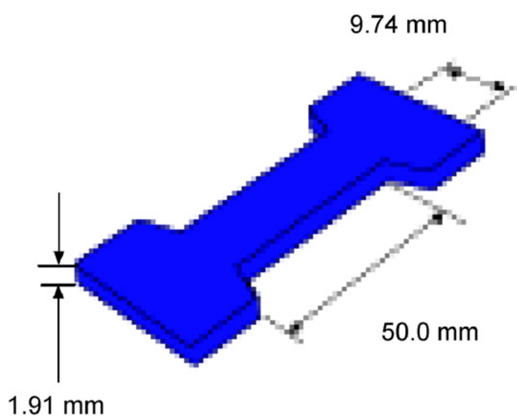

Fig. 1. Test specimen of polycarbonate with a gage length of 50 mm, a thickness of 1.91 mm and a width of 9.74 mm.

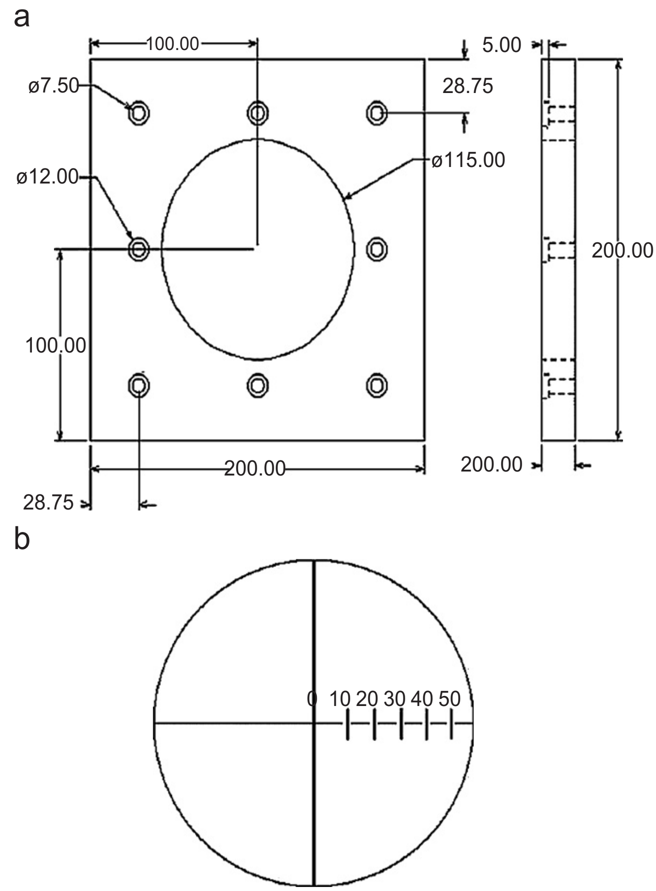

Fig. 3. (a) The polycarbonate plate secured between two plates with the help of screws. (b) The impact points starting from plate midpoint at 0 mm and terminating at 50 mm near the circular plate boundary.

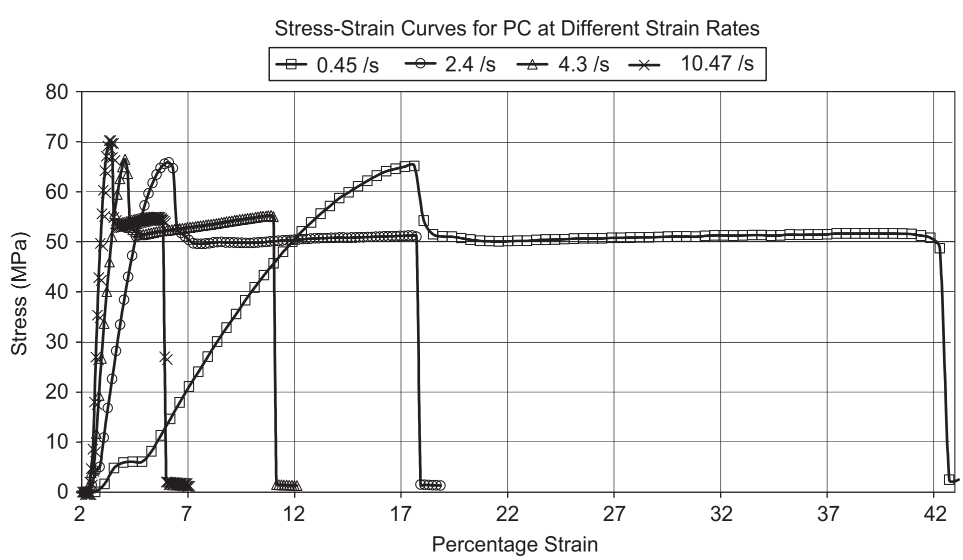

Fig. 2. The stress–strain curve of polycarbonate at various strain rates.

obtained was 63 MPa and the elastic modulus value was 1530 MPa. Poisson's ratio was found to be 0.38. Tangent modulus was calculated from the true stress–strain curve as 35 MPa.

A circular polycarbonate plate of 115 mm diameter and 1.91 mm thickness was secured between two rectangular plates with a hole as shown in Fig. 3a. A spherical steel projectile of 6.98 mm diameter was launched against the plate at a constant velocity of 138 m s^{-1} which was below the perforation limit of the target plate. The experiments were conducted at the midpoint of the plate and subsequent impacts were carried out at a distance of 10, 20, 30, 40, and 50 mm from the plate center, respectively. The impact points are shown in Fig. 3b. Deflection of the target plate, the dent size, and the thickness of the plate were recorded using an optical microscope for comparison purposes. The changes in thickness for impacts at 0, 10, 20, 30, 40, and 50 mm from the plate midpoint are shown in Fig. 4, respectively.

From the experiments, it was found that the variation in plate thickness for impacts starting from plate midpoint to the plate edge did not show any significant difference except for the impact close to the fixed edge that was at a distance of 50 mm from the midpoint. This can be observed in Fig. 4. For the impact at 50 mm distance from the plate midpoint a sudden change in plate thickness and dent depth were noticed. Moreover, it was found that if the edge constraints of target plate were strengthened by tightening the four jig screws shown in Fig. 1, the resulting plate thickness reduction for a constant projectile velocity was

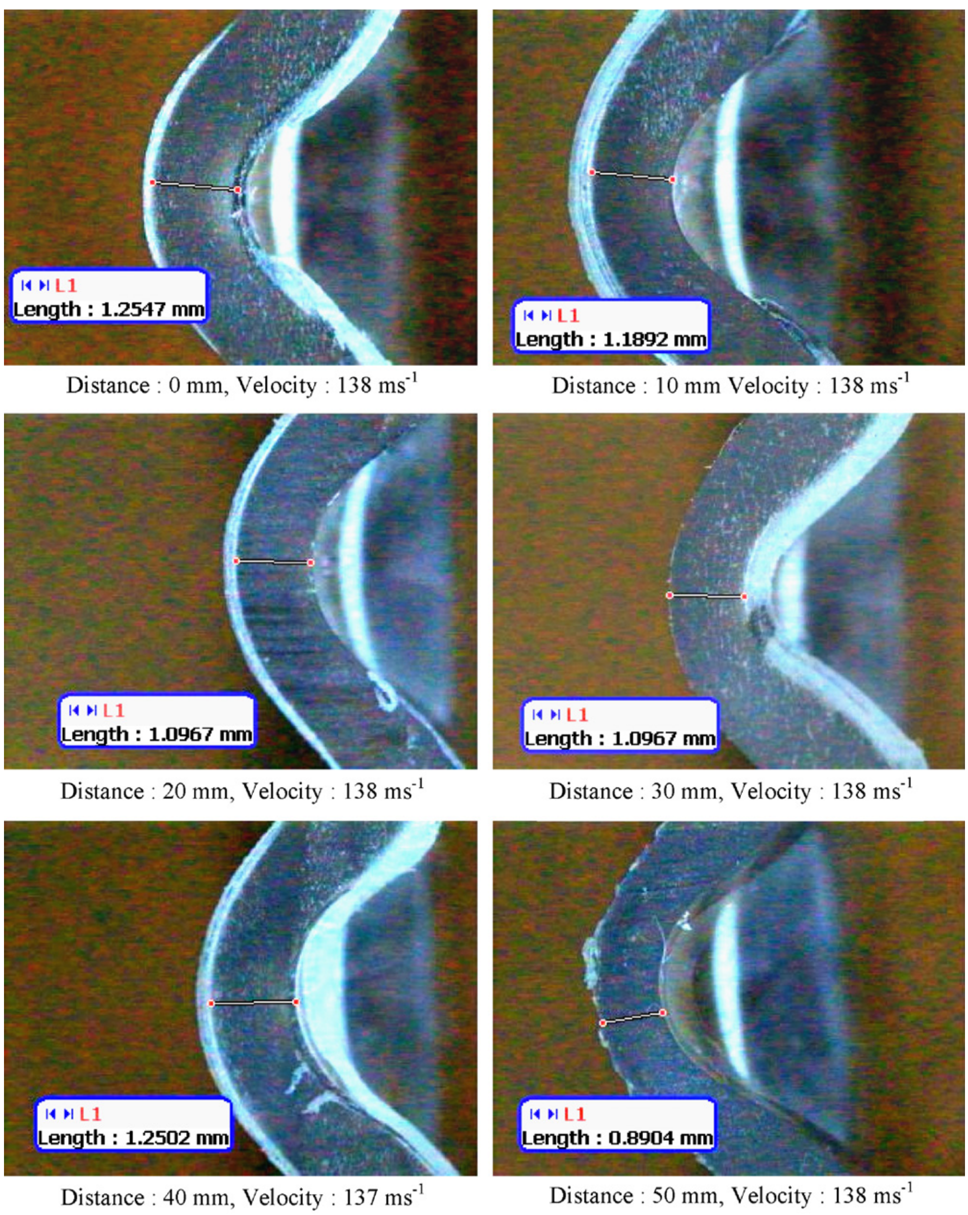

Fig. 4. The section view of the dent caused by projectile impact at a distance of 0, 10, 20, 30, 40, and 50 mm from the plate midpoint at a constant velocity of 138 m s^{-1}. Note that the velocity for the impact at 40 mm was 137 m s^{-1}.

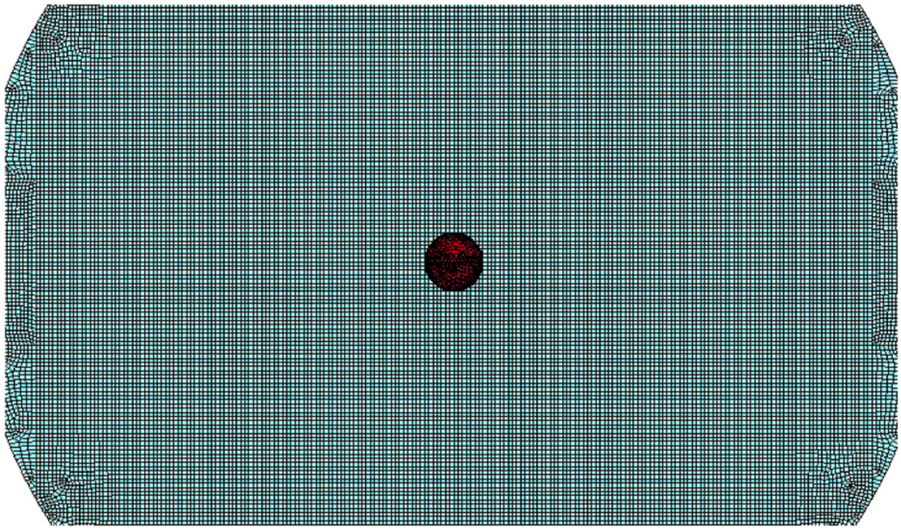

Fig. 5. A portion of the round target plate and rigid projectile mesh for finite-element simulation is shown.

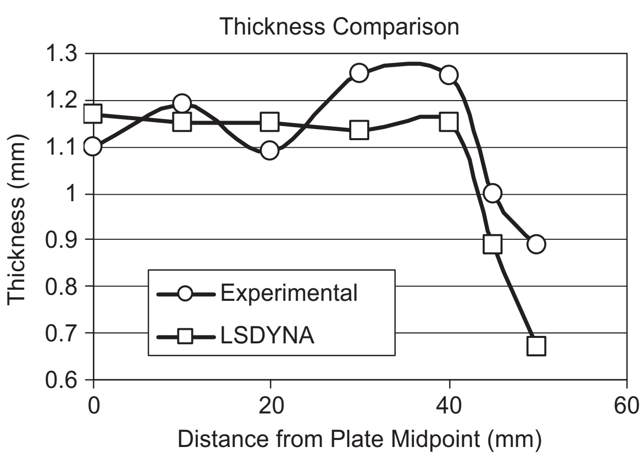

Fig. 6. The plate thickness obtained from experiments is compared with LSDYNA results.

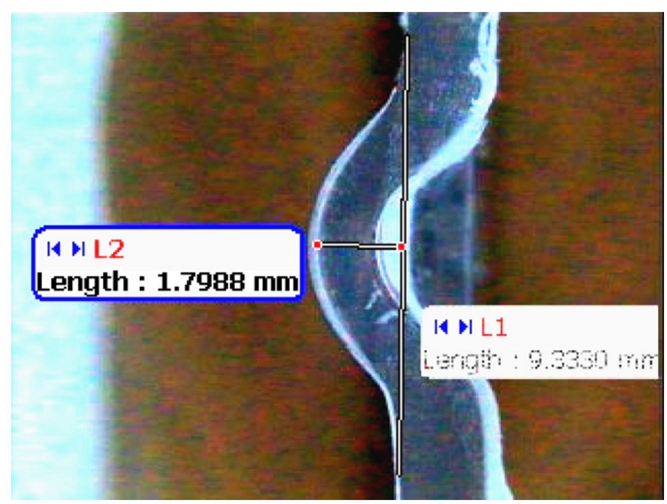

Fig. 8. The definition of the dent depth. It is the perpendicular distance from the undeformed back surface of the plate to the peak of dent arch.

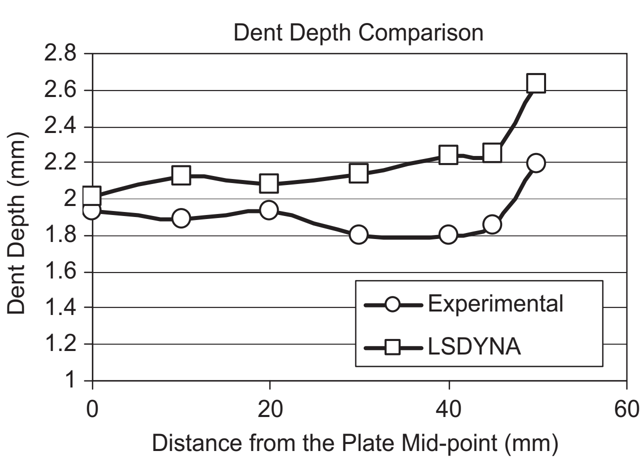

Fig. 7. The dent depth measured is compared with the dent depth obtained from simulations.

higher. The results are given in the discussion part of this report for comparison with simulation results.

3. Numerical analysis

The polycarbonate plate was modeled into LSDYNA with 41,751 shell elements. The impacting steel projectile was modeled as a rigid body with 7284 ten node solid elements. One portion of finite-element mesh is shown in Fig. 5. The target plate outer edge was constrained for all degrees of freedom. Projectile was launched against the target plate with an initial velocity of 138 m s^{-1}. Plate deflection, plastic strain, Von-Mises stresses, maximum shear stresses, plate thickness reductions, and energy absorption histories were recorded. Further impacts at locations 10, 20, 30, 40, 45, and 50 mm were carried out by shifting the projectile by 10 mm towards the boundary of the plate in each successive simulation.

The polycarbonate plate was modeled as *MAT_PLASTIC_KINEMATIC material in LSDYNA. For a single impact, the plate thickness and the dent depth can be compared very closely to the experimental results as shown in Figs. 6 and 7, respectively. Based upon this evidence, it can be envisaged that the rest of the results pertaining to plastic strain, stresses, and internal energy should match the experimental work. It was found from the comparison of experimental and LSDYNA constraints that the slight discrepancy in thicknesses is due to the inadequate constraints that cannot be achieved in experiments as precisely as they can be obtained in the simulations. In the simulation, there are large number of circular boundary nodes that are constrained for all degrees of freedom but the same cannot be done in experiments because of physical limitations.

If this point is not remembered during the simulation work, large variations could not be justified. In the present study once experimental results were obtained, they showed that the plate thickness was quite large compared to the thickness shown by LSDYNA at impact locations. When the support plates holding the target plate were tightened further with the help of screws as shown in Fig. 1, the experimental thickness variation matched well with the simulation results. Experiments were corrected with the help of simulation results.

Dent depth in this study is defined as the distance from the un-deformed back surface of the target plate to the peak of the spherical dent as shown for one case in Fig. 8.

The energy absorption history of the target plate for all the impacts at varying distances from the plate midpoint are shown in Fig. 9. The energy values for the midpoint impact show a noisy trend after the impact because the plate deflects in transverse direction is largest and it vibrates around the impact point severely after the impact as the midpoint of the plate is at the farthest distance from the support. The energy absorption history for the impact nearest to the fixed boundary shows a smooth curve revealing that the plate does not vibrate at points close to the constraint. The plastic strain history for all impacts is shown in Fig. 10. Though the simulation shows that there should be a perforation at 50 mm, the same was not possible in the experiments because the ideal dense node constraint conditions achievable in LSDYNA cannot be emulated in the experimental work due to non-rigid physical constraint.

The comparison of shear stresses in each impact is shown in Fig. 11. The maximum shear stress for the impact at 50 mm distance from the plate midpoint shows the highest

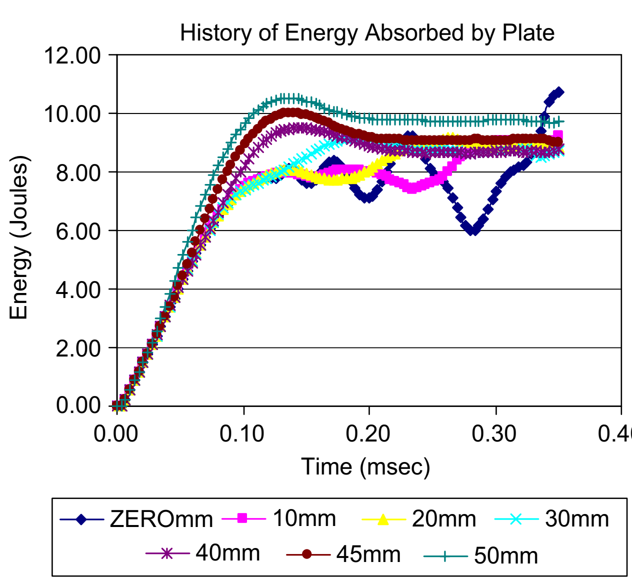

Fig. 9. The energy absorption history of the target plate for impacts from 0 to 50 mm distance from the plate midpoint.

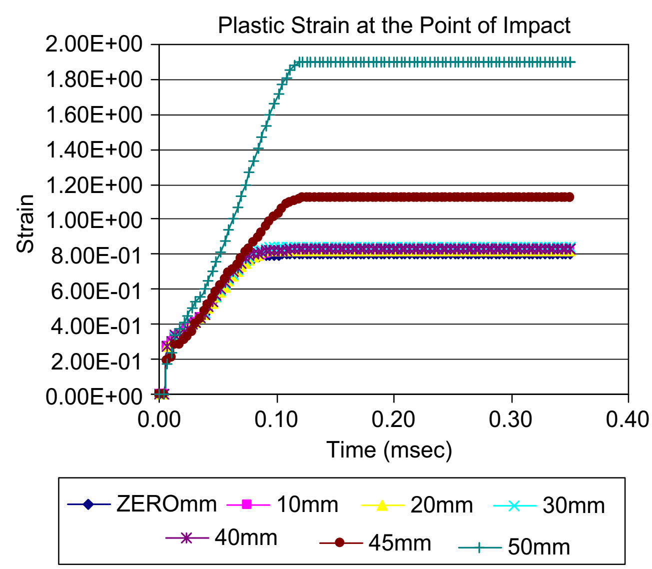

Fig. 10. The plastic strain history shows failure of the plate for an impact at 50 mm.

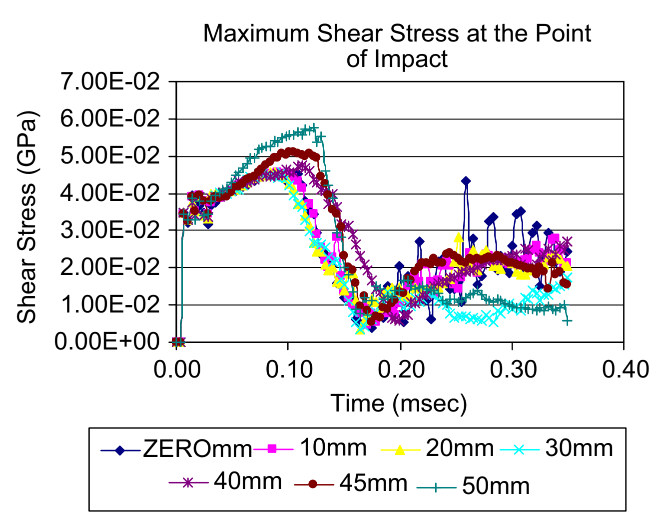

Fig. 11. Maximum shear stress history for each impact from 0 to 50 mm.

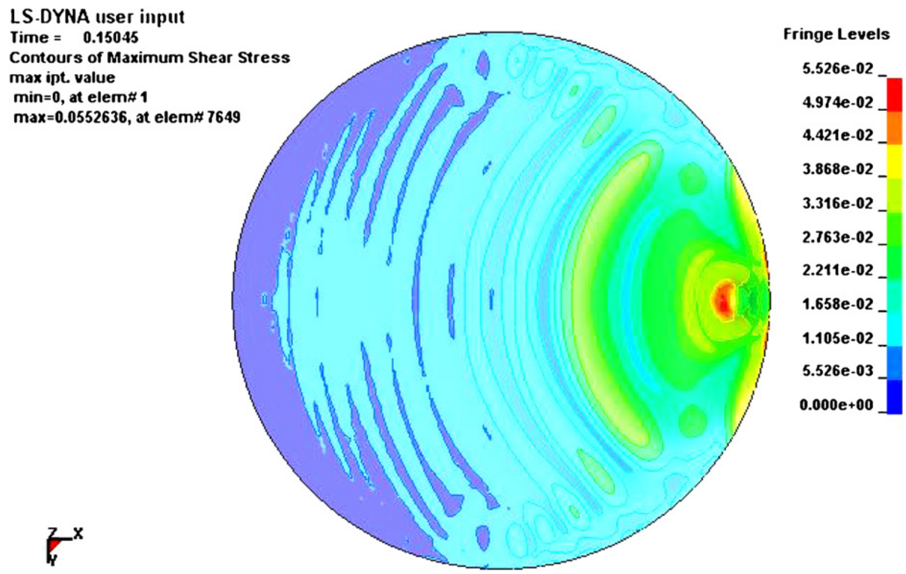

Fig. 12. Maximum shear stress plot shows the shear waves reflected from the plate boundary for 50 mm impact case.

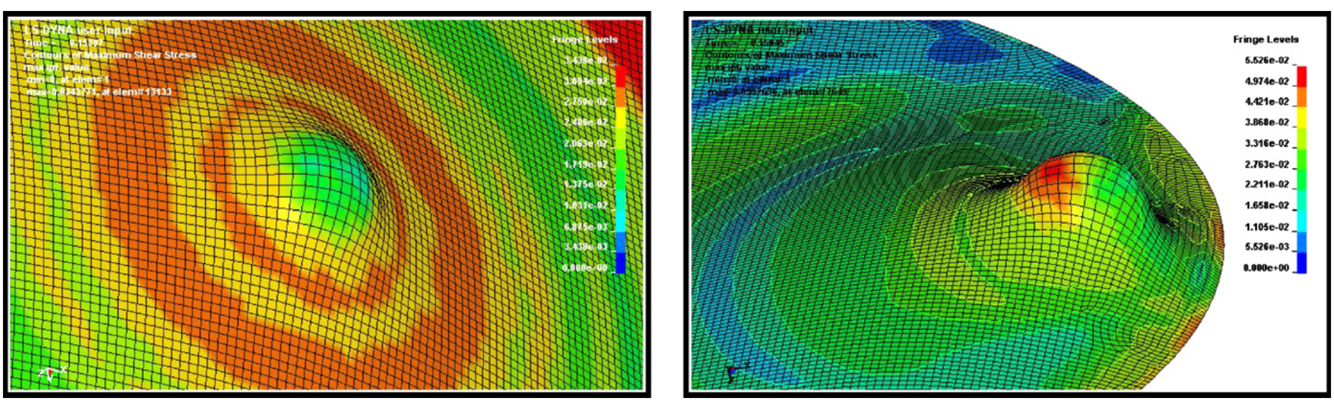

Fig. 13. The comparison of maximum shear stresses for impact case 30 and 50 mm.

values that can cause the failure at this point due to shearing process. This is because the plate material is constrained by the clamps at the plate edges. For the material model used in LSDYNA, the plastic strain and maximum shear stress [21] can account for the failure very precisely. The shear stress plot is shown in Fig. 12. The maximum shear stress plots for 30 and 50 mm impact cases are shown for comparison in Fig. 13.

4. Discussion

It is evident from Fig. 13 and the plate impact results that when the plate is impacted at its midpoint, more time and energy is consumed in deflecting the plate rather than causing localized dent deformation. For the impact at 50 mm distance from the midpoint that is in the immediate vicinity of the constrained edge, the localized deformation is very high as compared to the plate midpoint impact case. This is because due to rigid constraint the transverse plate deflection is minimized and all the projectile energy is consumed in local material deformation that results in a deep dent near to the plate edge.

When a projectile has no capability to perforate the target plate at its midpoint due to less kinetic energy that it possesses, its ability to perforate the target plate close to the supported edge must be determined to ensure the safety of the armor plate. If due to economic constraints the thicker material plate usage is prohibitive, an additional annular plate covering the plate surface near the clamped edge should be incorporated in the armor design.

5. Conclusion

Thin circular polycarbonate armor plate was subjected to a spherical projectile impact at the plate midpoint at a velocity of 138 m s^{-1}. At this velocity the projectile was able to cause a localized dent deformation of nearly 2 mm in the plate which was assumed to be safe under certain conditions. Successive impacts under similar conditions were repeated at locations of 10, 20, 30, 40, and 50 mm from the plate midpoint towards the clamped plate edge.

From plate midpoint to 40 mm position impacts, the dent sizes and the plate thickness reductions were noted to be roughly same. At a point very close to the outer edge, the plate thickness and the dent sizes increased significantly revealing the effect of distance from the plate midpoint on the damage mechanism.

The armor plate was modeled into finite-element and LSDYNA simulations agreed closely with the experimental work. Finite-element analysis showed a possible perforation initiation at the impact point close to the clamped edge. Using these results, the plate boundary was secured more firmly between two thick plates in the experimental work and it was found that the localized deformation matched the simulation results more closely. But to achieve the ideal boundary conditions as could be done easily in finite element, it was not possible experimentally with the existing jigs.

It is concluded that under a constant projectile velocity that is unable to cause any material separation in the mid-plate region, the plate perforation may be possible near the clamped edge of an armor plate. To prevent such failure close to the fixed edge it is suggested to incorporate an additional annular plate to cover the near edge zone.

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