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# Deformation behavior of the polycarbonate plates subjected to impact loading

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## Abstract

In the present work, the dynamic response of polycarbonate plates subjected to the projectile impact in different velocities was investigated. The plates were modeled with dimensions 400 mm × 400 mm and the thickness was taken of 2 mm. In addition, impact locations at plate center, 90 mm and 180 mm away from the center point were carried out by a spherical steel projectile. The numerical investigation of impact response of a polycarbonate plate is conducted by using LS-DYNA. Polycarbonate material behaves in an elastoplastic manner. Therefore, the plate was modeled using elastic-plastic material properties. A validation study was achieved by solving the impact response given in the literature and compared with the results. In numerical analysis, the plate was clamped at all edges and the impacting steel projectile was modeled as a rigid body. As a result, perforation and penetration behaviors of polycarbonate plates were investigated for different locations of the plates. In this way, maximum plastic strain, von Mises stresses, and energy absorbed by the plate were computed. The simulation results were evaluated and discussed in detail.

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*Keywords:* Polycarbonate plate; Impact; Perforation; Penetration.

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## 1. Introduction

Owing to its good impact resistance specialties, the polycarbonate material is used in helmets and bulletproof armored vehicles [1]. Polycarbonate (PC) is also under exploration for the progress and manufacture of sandwiched panels for bullet-proof waistcoats and armored systems where alternate layers of poly (methyl methacrylate) acrylic (PMMA) and polycarbonate are used to diminish the damage caused by high-velocity projectiles [2,3]. On account of their light weight, economical, even simple manufacturing processes, the usage of polymers is on the uptrend in a lot of industries. Experimental studies noticed on the attitude of polymers are not as numberless as on metals and numerical studies are even rare because of the absent of convenient material models [4-10]. Numerical studies on the reaction of shield systems made up of PC and PMMA were studied [5] where perfect particle hydrodynamics was used to simulate the response of PC and acrylic layers. It was studied that the ballistic resistance of fixed very thin PC sheets to single [5]. Layered materials are mostly used in applications involving impact protection. The mechanics of the beneficial influence provided by layering is not well understood in high strain rate situations. Therefore, dynamic failure of monolithic poly (methyl methacrylate) (PMMA) and polycarbonate (PC) plates subjected to impact loading were studied using an instrumented drop weight tower [11]. In another study, the plastic deformation of a thin rectangular polycarbonate armor plate subjected to single and multiple impacts was investigated [12]. It was concluded that reinforcements have to be provided close to the fixed edges. A study was made on sloped impact of poly (methyl methacrylate) (PMMA) thick sheets [13, 14]. Glazed polymers such as poly (methyl methacrylate) (PMMA) are a desirable choice for shield related applications owing to their material properties for instance pressure sensitivity, strain rate dependent strength, transparency, low density and very high durability [15]. In different study, a thick circular polycarbonate plate was impacted to spherical projectile and failure mechanism of armor plate was investigated [16]. In present study, target model was selected a square model. Similarly, impact event was started from plate center to clamped edge. Subsequent impacts were made at plate center, 90 mm and 180 mm. The plates were modeled using 400 mm × 400 mm size and 2 mm thickness. The paper is organized in the following way: First, verification study was accomplished and then the material properties and material model was mentioned in detail, followed by the numerical results.

## 2. Verification Study

For validation, a circular polycarbonate plate was used and it was impacted by a spherical steel projectile. 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. For a constant projectile velocity of 138 m/s which was below the perforation limit of the plate under investigation, a maximum thickness reduction close to the edge support was observed. This study was modeled into explicit finite-element analysis program LS-DYNA for simulations. The polycarbonate plate was modeled into LS-DYNA with 41751 shell elements. Maximum energy absorption and plastic strain values at plate center were recorded. Stress–strain curve obtained from the tension test at various strain rates. Failure strain was found to be 150% [16]. The material properties were given in Tables 1 and 2.

**Nomenclature**

| | |
|---|---|
| PC | Polycarbonate |
| PMMA | Poly (methyl methacrylate) |

Table 1.Material properties of PC [16].

| | |
|---|---|
| Density | 1200 kg/m$^3$ |
| Elastic Modulus | 1530 MPa |
| Poisson ratio | 0.38 |
| Yield Strength | 63 MPa |
| Tangent Modulus | 35 MPa |

Table 2.Material Properties of Projectile [16].

| | |
|---|---|
| Density | 7850 kg/m$^3$ |
| Elastic Modulus | 200 GPa |
| Poisson's ratio | 0.3 |

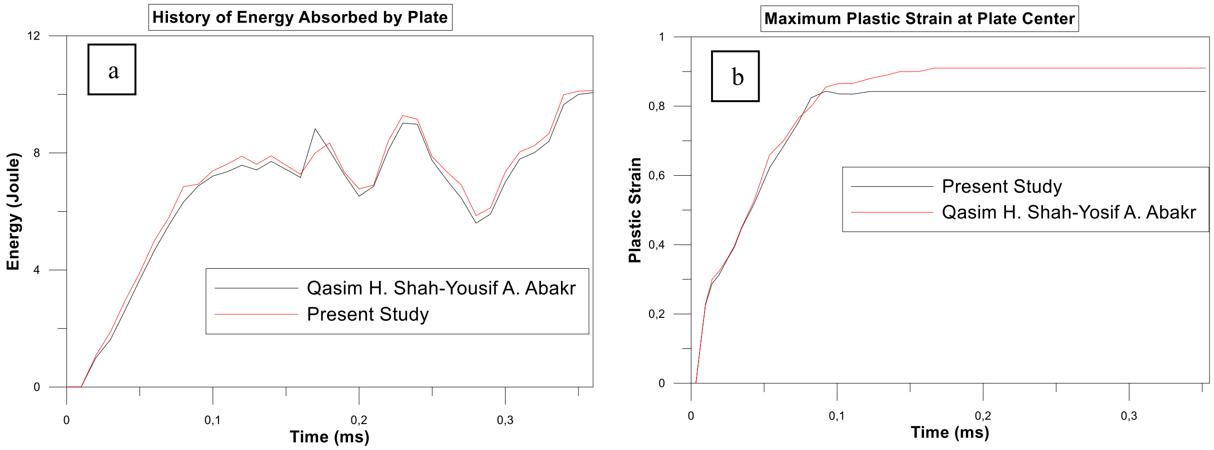

Fig. 1. a) Maximum plastic strain graph b) Energy absorbed by plate graph.

The energy absorption and maximum plastic strain distributions are given in Fig 1. It can be understood that both energy absorption and plastic strain values in present study are close to literature. It is concluded that under a constant projectile velocity that is unable to cause any material separation in the plate center region. According to results, it can be said that verification study has been implemented successfully.

## 3. Numerical Simulations

The numerical simulations were carried out using LS-DYNA explicit finite element code. The type of analysis, geometry, material properties, failure criteria and mesh are detailed in the sequel.

### *3.1. Geometry*

The plate was modeled with dimensions 400 mm×400 mm and 2 mm thickness. Subsequent impacts were conducted at plate center, 90 mm and 180 mm away from the center of the plate. The exposed area of the polycarbonate armor plates with impact locations on the horizontal paths is shown in Fig. 2.

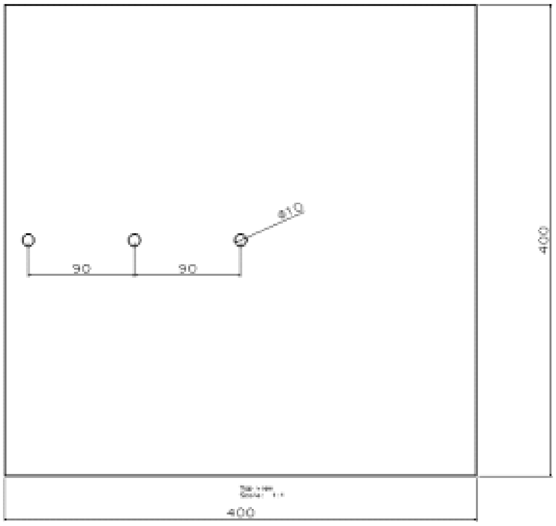

Fig. 2. The exposed area of the plates with impact locations on the horizontal paths.

A spherical steel projectile of 10 mm diameter was launched against the square plate. The spherical steel projectile was selected from LS-DYNA menu as rigid model in this study. Also, projectile velocities of 50, 80 and 120 m/s were determined.

### *3.2. Material properties and failure criteria*

Polycarbonate and steel projectile properties used in this study were given in Table 1 and 2. The material properties available for polycarbonate material at high strain rate found in the literature were very rare and material models in most cases were incomplete or lacked precision [16]. Polycarbonate tensile tests were therefore performed on the test coupon. Stress–strain curve obtained from the tension test at various strain rates. Failure strain was found to be 150% [16]. A low capability polymer testing machine was used to conduct the tensile tests. At low loading rate the strain to failure is observed to be large but for dynamic loads the strain to failure is smaller. As is evident from the stress–strain curves the elastic modulus at higher strain rates increases significantly unlike most metals. The curve with the largest failure strain was obtained from the static tensile test [12]. The rest of the curves were obtained for higher strain rates. As the strain rate enhances the yield strength increases but for polymers it remains constant after a certain strain rate. Even though the material properties used were obtained at lower strain rates than the actual material properties that are required to be conducted at higher strain rates [12] that are matched in bullet impacts, the results still closely agree with the experimental investigations.

### *3.3. Material models*

The polycarbonate plate was modeled into LS-DYNA with approximately 167000 shell elements. The target plate outer edge was constrained for all degrees of freedom. Projectile was launched against the target plate with different initial velocities of 50, 80 and 120 m/s. Plastic strain, von Mises stresses, maximum shear stresses and energy absorption histories were recorded. Further, impacts locations at plate center, 90 and 180 mm were carried out by a spherical steel projectile diameter of 10 mm. The material model used for the polycarbonate target plate was Kinematic Hardening.

## **4. Numerical Results**

The numerical results were compared according to different impact locations and different projectile velocities for polycarbonate materials. These results were given in graphics and table. Firstly, the steel projectile velocity was selected as 50 m/s. Then, 80 and 120 m/s velocities were used respectively. von Mises Stresses at the center of polycarbonate plate with 2 mm thickness is shown in Fig. 3. The yield stress of polycarbonate is 63 MPa and it was obtained as 67.42 MPa after the impact load. Thus, it was occurred plastic deformation as expected. It is also given that von Mises Stress distribution at plate center, 90 and 180 mm in Fig. 4a. Maximum von Mises Stress at 90 mm distance is 67.23 MPa. Further, von Mises Stress distribution at 180 mm is 76.09 MPa. It is also observed that the maximum plastic strain values on polycarbonate plates at different impact points. Plastic strain value at plate center is 0.34. Plastic strain value at 90 mm distance is 0.34 and also at 180 mm distance from plate center is 0.38. It is shown that plastic strain distribution at plate center, 90 and 180 mm in Fig. 4b. The energy absorption histories of the target plate for all impact points are given below. It was shown that energy absorption at plate center, 90 and 180 mm in Fig. 4c. The energy absorption at plate center was 3.06 joule. The energy absorption at 90 mm was 2.88 joule. In addition, the energy absorption at 180 mm was 3.44 joule.

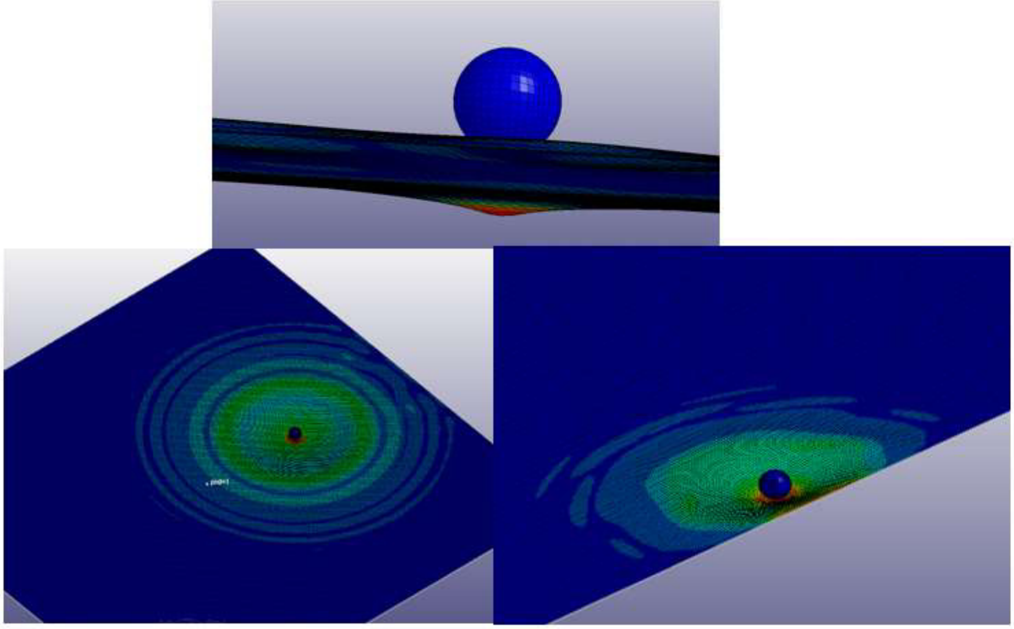

Fig. 3. von Mises Stress distribution at different impact points.

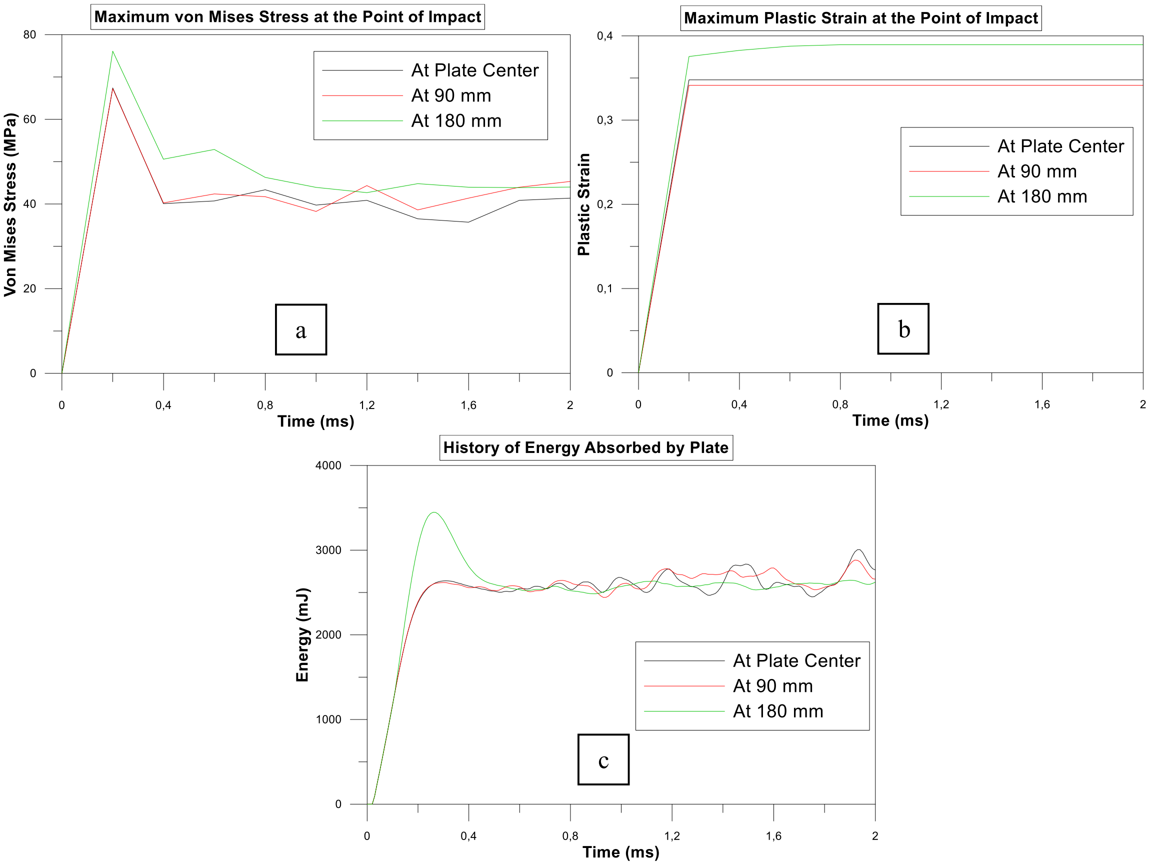

Fig. 4. a) von Mises Stress graph b) Plastic strain graph c) Absorbed energy graph.

It is given all conclusions at different velocities in Table 3, 4 and 5.

Table 3.Maximum von Mises Stress values.

| | Velocities (m/s) | | |
|---|---|---|---|
| **Impact Locations** | **50** | **80** | **120** |
| **Plate Center (MPa)** | 67.42 | 63.43 | 56.94 |
| **At 90 mm (MPa)** | 67.23 | 63.74 | 56.66 |
| **At 180 mm (MPa)** | 76.09 | 77.02 | 77.68 |

Table 4.Maximum plastic strain values.

| | Velocities (m/s) | | |
|---|---|---|---|
| **Impact Locations** | **50** | **80** | **120** |
| **Plate Center** | 0.34 | 0.42 | 0.59 |
| **At 90 mm** | 0.34 | 0.41 | 0.59 |
| **At 180 mm** | 0.38 | 0.45 | 0.63 |

Table 5 .The energy absorption history.

| | Velocities (m/s) | | |
|---|---|---|---|
| **Impact Locations** | **50** | **80** | **120** |
| **Plate Center (Joule)** | 3.06 | 7.77 | 18.74 |
| **At 90 mm (Joule)** | 2.88 | 7.43 | 18.23 |
| **At 180 mm (Joule)** | 3.44 | 8.67 | 20.52 |

## 5. Conclusions

The square polycarbonate plate was subjected to a spherical projectile impact at varying velocities. The projectile velocities are 50, 80 and 120 m/s respectively. Successive impacts under similar conditions were conducted at locations of plate center, 90 and 180 mm distances. Since square plate edges were constraint, it was occurred that higher stress at close to fixed edge than other impact locations as expected. Further, maximum plastic strain increased toward clamped edge for all projectile velocities. It was observed that large deformations at all impact points are occurred. At close to clamped edge, stress and strain values may cause perforated event. Therefore, it was possible to be perforated at near the fixed edge. For polycarbonate plates at different velocities, maximum energy absorption shows the highest values at 180 mm. At all impact points, there was no perforation for all projectile velocities. The reason for no perforation at the plate midpoints is due to the fact that the plate can deflect freely to a large lateral distance therefore absorbing more energy in plate failure mechanism. For a certain projectile velocity which cause only an acceptable plastic deformation at the plate midpoints the deformation near the firmly clamped edge was significantly higher for an impact event. Also, it was observed that for the impact at 180 mm distance from plate center that is in the vicinity of the constrained edge, the localized deformation was very high as compared to the plate midpoint impact case. This is because due to rigid constraint the transverse plate deflection was minimized and all the projectile energy was consumed in local material deformation that results in a deep dent near to the plate edge. As it is clear from the above mentioned discussion that the impact points near the fixed straight edge is the crucial locations for the possible earlier failure, it was decided to investigate the plate center, 90 mm and especially 180 mm distance from plate center. It was understood that polycarbonate material is more impact resistance than many other polymeric materials. However, when designing the rectangular or square armor plates made up of a ductile polymer like polycarbonate, special care must be taken for the protection against the projectile striking near the clamped straight should be provided near the clamped edges. Some impact points were occurred that penetration and perforation for polycarbonate plates. In order to prevent such failure especially close to clamped edge it is suggested to incorporate an additional plate to cover the near edge zone. There might be conducted future works such as an experimental study of the comparison of polycarbonate material.

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