Ballistic performance evaluation of polycarbonate plate based on quasi-static perforation

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Abstract. The present work deals with the experimental investigation involving Quasi-static perforation of thin circular polycarbonate plate for ballistic performance evaluation. Effective diameter and thickness of polycarbonate plate is 205 mm and 2.66 mm respectively. Quasi-static perforation is performed on Servo-mechanical universal testing machine of capacity 50 kN using Blunt and Truncated cone penetrators of diameter 12.8 mm made of EN31 alloy steel. The velocity of the penetrator (indenter) is set at 2 mm/min and the impact is carried out at the centre of the plate. The results obtained based on Quasi-static tests are used in conjunction with the impact test performed using pneumatic gun set-up [1] for the same set of target plate and projectile nose shape. The ratio of the dynamic and quasi-static perforation energy defined as dynamic enhancement factor has been calculated. The variation of dynamic enhancement factor (DEF) with the impact velocity exhibit a linearly increasing pattern similar to those in literature for metallic plates [2].

1. Introduction

Owing to good strength to weight ratio, better static/impact resistance and transparent properties of polycarbonate, it is widely used in household and industrial application. During service/application the components made of polycarbonate may often be subjected to impact loads and it becomes necessary to investigate their ballistic performance. The behavior of polycarbonate (PC) and aluminium plate subjected to impact of projectiles of various nose shapes have been carried out by various researchers [1, 3-6]. These studies deal with estimation of ballistic limit and deformation mechanism at high velocities. The experimental and numerical investigation of impact on polycarbonate plates has been carried out by the authors [1]. The quasi-static deformation behavior of polycarbonate plates investigated in this paper, probably has not been studied earlier. The quasi-static perforation energy has been computed and is compared with the dynamic perforation energy [1]. Further the dynamic enhancement factor is calculated showing linear variation with the impact velocity where it can be seen that the increase of DEF with the increase in impact velocity is greater for truncated cone projectiles compared to blunt nose shape projectiles.

2. Experimental procedure

In the present study blunt and truncated cone penetrator (Fig. 1) of 12.8 mm diameter and total length of 25.6 mm and 28.8 mm, respectively are employed for the quasi-static test on UTM. The penetrators are machined from EN31 alloy steel to the required shape and then hardened by raising the temperature
to 920°C followed by oil quenching. The hardness of the impactors are tested on Rockwell hardness testing machine where the hardness is found to be in the range of 64-65 Rh. The desired hardness of 47-50 Rh is achieved by tempering. The nose shape of penetrators are kept same as the nose shape of projectiles used in dynamic impact test of the authors [1].

![Penetrators](image)

**Fig. 1** Camera and schematic view of penetrators

The diameter of polycarbonate plate is 255 mm and thickness is 2.66 mm. Eight holes are drilled on pitch diameter of 230 mm on target plate to securely hold the target plate between two rings and effective diameter is 205 mm (Fig. 2).

### 2.1. Quasi-static perforation test setup.

The servo-mechanical universal testing machine of load capacity 50 kN is used to perform quasi-static test. The target plate is sandwiched between two rings of 205 mm internal diameter and penetrator is positioned at the center of the target plate as shown in Fig. 3. The speed of the penetrator is set at 2 mm/min which is positioned to perforate the sandwich structure at the center. Force-displacement data recorded from the servo-mechanical UTM for both shapes of the penetrator is shown in Fig. 4. The area under the force-displacement curve is calculated to get the energy absorbed in perforating the plate for both types of the projectiles. The evaluated data from force displacement curve is tabulated in Table 1.

![PC Plate Schematic](image)

**Fig. 2** Schematic diagram of PC Plate

![Experimental Setup](image)

**Fig. 3** Experimental setup of quasi-static perforation
Fig 4. Force-Displacement curves for blunt and truncated cone penetrators.

Table 1. Properties from quasi-static force displacement curve

|                           | Blunt penetrator | Truncated cone penetrator |
|---------------------------|------------------|---------------------------|
| Maximum force applied (N) | 4702             | 5639                      |
| Energy absorbed (J), $E_s$| 57.8             | 58.2                      |

3. Results and Discussion

Quasi-static perforation is performed on thin circular Polycarbonate plate of diameter 255 mm and thickness 2.66 mm. Two different penetrators of blunt as well as truncated cone nose shape are used in the current experimental study. Energy absorbed in perforating the target plate in quasi-static perforation ($E_s$) by blunt nose shape and truncated nose shape penetrators are obtained as 57.8 J and 58.2 J respectively.

The results obtained from the quasi-static perforation tests are compared with the results obtained from the dynamic impact test performed by the authors [1] on a pneumatic gun setup for the same set of penetrators (projectiles) and PC target plate. The ratio of the dynamic and quasi-static perforation energy defined as dynamic enhancement factor (DEF) is calculated for both types of penetrators. The experimental results obtained from the dynamic impact test [1] and the corresponding DEF based on quasi-static tests for blunt and truncated cone projectile shapes are tabulated in Table 2 and 3, respectively.

The variation of dynamic enhancement factor with the impact velocity for blunt as well as truncated cone penetrators is presented in Fig. 5. A linear relationship is obtained between the DEF and impact velocity for both the nose shape penetrators. An empirical relation has been developed for both blunt (Eq. 1) and truncated conical (Eq. 2) penetrators governing the variations of DEF with respect to the impact velocity.

$$\text{DEF for blunt penetrators} = \frac{E_d}{E_s} = 0.0022 V_i + 1.3629$$  \hspace{1cm} (1)

$$\text{DEF for truncated cone penetrators} = \frac{E_d}{E_s} = 0.0179 V_i - 0.3456$$  \hspace{1cm} (2)
Table 2. Experimental dynamic impact test result [1] and Dynamic enhancement factor based on quasi-static test for blunt penetrators.

| S.No | Impact Velocity, $V_i$ (m/s) | Residual Velocity, $V_r$ (m/s) | Impact Energy (J)       | Absorbed Energy (J) (Dynamic Impact Test) $E_d$ | Dynamic Enhancement Factor (DEF) $E_d/E_s$ |
|------|-----------------------------|-------------------------------|------------------------|-----------------------------------------------|----------------------------------------|
| 1    | 106.19                      | 64.25                         | 143.77                 | 91.14                                         | 1.58                                   |
| 2    | 105.26                      | 62.15                         | 141.27                 | 92.02                                         | 1.59                                   |
| 3    | 101.69                      | 55.23                         | 131.85                 | 92.95                                         | 1.61                                   |
| 4    | 98.36                       | 49.79                         | 123.35                 | 91.74                                         | 1.59                                   |
| 5    | 88.24                       | 34.12                         | 99.28                  | 84.43                                         | 1.46                                   |
| 6    | 85.71                       | 0                             | 93.66                  | 93.66                                         | 1.62                                   |

Table 3. Experimental dynamic impact test result [1] and Dynamic enhancement factor based on quasi-static test for truncated cone nose shape penetrators.

| S.No | Impact Velocity, $V_i$ (m/s) | Residual Velocity, $V_r$ (m/s) | Impact Energy (J) | Absorbed Energy (J) (Dynamic Impact Test) $E_d$ | Dynamic enhancement factor (DEF) $E_d/E_s$ |
|------|-----------------------------|-------------------------------|-------------------|-----------------------------------------------|----------------------------------------|
| 1    | 104.35                      | 62.2                          | 138.83            | 89.51                                         | 1.54                                   |
| 2    | 97.56                       | 57.19                         | 121.35            | 79.65                                         | 1.37                                   |
| 3    | 92.31                       | 48.95                         | 108.64            | 78.09                                         | 1.34                                   |
| 4    | 91.6                        | 48.55                         | 106.98            | 76.93                                         | 1.32                                   |
| 5    | 85.11                       | 47.19                         | 92.36             | 63.96                                         | 1.10                                   |
| 6    | 76.43                       | 31.44                         | 74.48             | 61.88                                         | 1.06                                   |

Fig 5. Variation of Dynamic Enhancement Factor with impact velocity
The deformed configuration of polycarbonate plates impacted by blunt impactors, after perforation under dynamic impact test using pneumatic gun set-up corresponding to impact velocity of 98.36 m/s and the corresponding deformed configuration under quasi-static loading with the same projectile is shown in Fig. 6.

Fig. 6 Deformed configuration of the polycarbonate plate after perforation impacted by blunt projectile (a) Dynamic impact test on pneumatic gun setup at impact velocity of 98.36 m/s (b) Quasi-static impact test on UTM.

Fig. 7 Deformed configuration of the polycarbonate plate after perforation impacted by truncated conical projectile (a) Dynamic impact test on pneumatic gun setup at impact velocity of 91.6 m/s (b) Quasi-static impact test on UTM.
The deformed configuration of polycarbonate plates impacted by truncated conical impactors, after perforation under dynamic impact test using pneumatic gun set-up corresponding to impact velocity of 91.6 m/s and the corresponding deformed configuration under quasi-static loading with the same projectile is shown in Fig. 7.

The deformed configuration for both blunt as well as truncated conical projectile reveal greater tearing damage at the back face under quasi-static test compared to dynamic impact test.

The dynamic enhancement factors calculated for blunt as well as truncated cone nose shape projectiles shows linear variation with impact velocity similar to those reported in the literature for sandwich metallic plates by Hou et al. [2].

4. Conclusion

Quasi-static perforation tests have been performed on servo-mechanical UTM and perforation energies have been obtained for blunt as well as truncated conical penetrators, impacting a PC plate. The dynamic enhancement factors have been calculated from the quasi-static perforation energy and the dynamic perforation energy obtained by the authors [1] from tests on the same set of impactors and PC plate using pneumatic gun setup. A linear relationship has been obtained between the DEF and impact velocity for both blunt as well as truncated projectiles and empirical relations relating the DEF with impact velocity has been proposed based on the experimental data. Typical plots depicting the deformed configuration of perforated plates under dynamic as well as quasi-static tests have been presented which reveal greater tearing damage at back face for quasi-static loading. It can be seen that dynamic impact causes the perforation energy to increase significantly for both blunt as well as truncated conical penetrators.

References

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