Experimental Study of Polyurea Protective Coating Effectiveness for Layered Composite Material Reinforced by Glass-Fiber under Impact Loading

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Abstract. One of the promising methods for increasing the resistance of polymer composite materials to high-speed impact is the use of protective shockproof coatings. At the same time, over the past two decades, polyurea have been gaining noticeable popularity among such coatings. This work is devoted to study the effect of polyurea coating of 1.2 mm thickness on ballistic resistance characteristics of glass-fibre reinforced layered polymer of 8.5 mm thickness. During the experiments thirteen composite targets was affected by high-speed impact loading in the range of 80…150 m/s by spherical steel projectile of 23.8 mm diameter. It was shown that using the polyurea coating can increase the ballistic limit by 19% increasing the mass of the target only by 7%. Dynamic strain and displacement fields on the back surface of the target was obtained using digital image correlation method for 81.2 m/s collision process.

1. Introduction
Since the end of last century it is known that polyurea coatings can increase corrosion and wear resistance of structures. But nowadays a lot of studies have shown that they can also effectively protect various heavy industry applications and structures from explosion and impact. The use of polyurea for protection of concrete walls is described in the publications of Davidson J.S. et al., Iqbal N. and Szafran J. et al in 2005-2018 [1-3]. Such coatings can prevent fragments from breaking off on the back side of the wall in the event of an explosion. In works of Amini M.R. et al. it was shown in numerical and experimental study that polyurea can lead to a significant effect on the response of the steel plate to dynamic impulsive loads, both in terms of failure mitigation and energy absorption when applied on the rear surface of the target [4, 5].

In work of Tekalur S.A. et al. (2006) one of the analogues of polyurea – polyurethane was studied to evaluate the effect of protection against explosive load it can perform for GFRP plate [6]. It was shown that adding a polyurethane layer on the front surface can significantly increase impact resistance. In addition, it was also shown, that sandwich composite-polyurea-composite structures had better impact resistance that simple composite laminates. In 2014 by LeBlanc J. et al was described a numerical and experimental study to evaluate the response of GFRP plate with polyurea coating to an explosion.

As a conclusion from this introduction, we can say that polyurea is able to increase the resistance of structures to high-speed impact and explosive loads, but the mechanisms of this effect have not yet been fully investigated. Therefore, this article is devoted to assessing the effectiveness of the use of a protective coating made of polyurea for the protection of a laminated polymer material based on glass fibers.
2. Experimental method

2.1. Object of study

Thirteen GFRP samples (Fig. 1) were made of 42 layered fiberglass weaved fabric with an epoxyphenol resin matrix. All the samples were made in the form of a rectangular plate with a size of 200 × 300 × 8.5 ± 0.1 mm and with a mass of 0.925 ± 0.005 Kg. The resultant material has the 1825.57 Kg/m³ density. Seven of thirteen samples were covered with a polyurea coating of 1.2 ± 0.05 mm thickness and 0.069 ± 0.002 Kg mass, so the areal density of such coating was about 1.15 kg/m².

During the preparation of the ballistic experiments the series of mechanical tests were made to obtain $\sigma$, MPa - $\varepsilon$, % diagrams for GFRP and polyurea specimens. As a result tensile strength of 353.3 ± 0.5 MPa for the directions [0] and 305.5 ± 4.1 MPa for the directions [90] was obtained for GFRP base material. So the maximum strains before failure was 1.78 ± 0.1% and 1.84 ± 0.01% for the directions [0] and [90] respectively.

The mechanical properties of the polyurea coating strongly depend on the rate of deformation. The tensile strength and fracture strain at the loading speed of 60 mm/min were 21.7 MPa and 142%, and for a loading speed of 3000 mm/min they reach 32 MPa and 79%, with 32 mm measuring base for both experiments.

2.2. Experimental test rig and procedure

The experimental setup (Fig.2 a) is a set of equipment, consisting of: loaded sample - 1; booster pneumatic module - 2; laser sensor to measure velocity of the projectile - 3; two high-speed cameras - 4, data collection and processing systems - 6; and a personal computer - 7. Analysis of the dynamics of the sample and the projectile was carried out on the basis of video data obtained with the help of high-speed cameras, which record the impact process in a top view and at an angle with a shooting rate of 45,000 frames per second. The dynamic strain and displacement fields were assessed using the DIC method while shooting the sample at 60,000 frames per second from the rear side (Fig. 2 b). Impact loading was carried out in the range of speeds from 80 to 150 m/s. At the same time, the use of the DIC method was possible only at the lower limit of the range of realized collision velocities at which the rear side of the specimen was not affected by the fracture. Detailed description of the experimental setup was given in [8-10]. As a projectile the steel spherical ball with a diameter of 0.0238 m and nominal mass 0.0547 kg was used.

During the experimental study, the samples were clamped at the bottom from one end (Fig. 3, a) and ballistic loading was carried out at the point P0 in the center of their free part. The idea of the experiment
was to compare the values of the safe collision speed of the projectile and the for target with (i) no coating, (ii) for target coated on the front surface, and (iii) for target coated on the back surface. For each type of loading, the experiment began with the minimum expected impact velocity, which should not have resulted in the specimen breaking through. Then the speed of the projectile was increased stepwise by 8.5 m/s until penetration was obtained. Thus the range of impact velocities for uncoated samples (Fig. 3, b) was 97 ... 128 m/s. For samples with a coating on the front surface (Fig 3, c) the range was 127.8 ... 150 m/s, and for samples with a coating on the back surface (Fig 3, d) 128.1 ... 135 m/s.

In addition, single shot was made at speed 81.2 m/s using digital image correlation method for loading case with no coating (Fig.3, b). This speed was chosen for the reasons of minor intra- and interlayer fracture appearance during the evaluating of dynamic strain and displacement fields. The main idea of that was that minor fracture will affect less on the resultant dynamic characteristics of the target that will be evaluated during the numerical model identification based on digital image correlation data, if such identification will be held in future.

The assessment of the fracture of the samples was carried out based on the analysis of the geometric characteristics of the cracks on the specimen’s surface and delamination zones.

3. Results and discussion

Full breakdown of the experiment is shown in the Table 1. The table shows the velocities of the projectile before and after collision, as well as the calculated values of the initial and residual kinetic energies of the striker and the values of the energies absorbed by the samples. Negative values of the residual velocity of the striker mean that during the impact it bounced off the target in the opposite direction.

As we can see, for the case of loading samples without any protective coating, the obtained value of the maximum safe collision velocity is 120.6 m/s. At the next stage of loading at a collision speed of 128.1 m/s, the target was already pierced and this speed can no longer be considered safe.
When a protective polyurea coating was applied to the front surface of the sample, the value of the safe impact velocity increased noticeably to 142.8 m/s. At the same time, the value of the energy that can be absorbed by the sample upon collision without penetration also increased to 545.75 J against the value of 392.55 J, which was obtained for the uncoated sample.

When the coating is applied to the rear surface, the resulting safe impact velocity is almost the same as that obtained for the uncoated specimen and is 120.3 m/s. An insignificant increase in the value of the absorbed energy (15.5 J) upon collision at a velocity of 128.1 m/s (11-th test) compared to the value obtained for the uncoated sample (4-th test) is most likely associated with the energy consumption for fracture and deformation of the polyurea layer on the back side of the sample.

Thus, the application of a protective coating made of polyurea with a thickness of 1.2 mm on the front surface of the fiberglass sample made it possible to increase the safe impact speed by 24.2 m/s (19%) with an increase in the sample weight by only 0.070 kg (7%).

Table 1. Experimental results summary

| Test № | Coating location | Initial velocity (m/s) | Incident energy (J) | Residual velocity (m/s) | Residual energy (J) | Absorbed energy (J) | Penetration |
|--------|------------------|------------------------|---------------------|-------------------------|---------------------|---------------------|-------------|
| 1      | No coating       | 97.6                   | 261.20              | -14.9                   | 6.09                | 255.11              | No          |
| 2      | Face             | 135.2                  | 499.73              | 55.9                    | 85.68               | 414.05              | Yes         |
| 3      | Face             | 120.6                  | 398.81              | -15.1                   | 6.25                | 392.55              | No          |
| 4      | Face             | 128.1                  | 449.95              | 28.6                    | 22.43               | 427.52              | Yes         |
| 5      | Face             | 127.8                  | 447.85              | -14.8                   | 6.01                | 441.84              | No          |
| 6      | Face             | 134.8                  | 498.25              | -16.7                   | 7.65                | 490.60              | No          |
| 7      | Face             | 142.8                  | 559.14              | -22.1                   | 13.39               | 545.75              | No          |
| 8      | Face             | 150                    | 616.95              | 48.7                    | 65.03               | 551.92              | Yes         |
| 9      | Face             | 135.2                  | 501.21              | 58                      | 92.24               | 408.97              | Yes         |
| 10     | Back             | 120.3                  | 396.82              | -19                     | 9.90                | 386.93              | No          |
| 11     | Back             | 128.1                  | 449.95              | 16                      | 7.02                | 442.93              | Yes         |

When a protective polyurea coating was applied to the front surface of the sample, the value of the safe impact velocity increased noticeably to 142.8 m/s. At the same time, the value of the energy that can be absorbed by the sample upon collision without penetration also increased to 545.75 J against the value of 392.55 J, which was obtained for the uncoated sample.

Figure 4 – Out-of-plane displacements [mm] to time [ms] dependencies for P0, P1, P2 points on the back surface of the target.

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Thus, the application of a protective coating made of polyurea with a thickness of 1.2 mm on the front surface of the fiberglass sample made it possible to increase the safe impact speed by 24.2 m/s (19%) with an increase in the sample weight by only 0.070 kg (7%).
Figure 4 shows the time dependences of displacements in the direction of the axis perpendicular to the target plane, obtained using the digital image correlation method, for three different points on the target's axis of symmetry (Fig. 3 a): (i) on the rear surface of the sample at the point of collision - P0; (ii) at a distance of 5 mm from the peripheral section of target - P1; (iii) and at 5 mm from the embedment - P2. This data was obtained for the projectile collision speed of 81.2 m/s. We can observe multi-harmonic damped oscillations made by target after impact, with maximum displacements on the first oscillation cycle of 21, 12 and 1.2 mm for points P1, P0 and P2, respectively. For each of the obtained time dependences, the period of damped oscillations is approximately 14.5 ± 0.5 ms. This data can be used to identify the dynamic elastic characteristics of the target specimen during the identification of the numerical model of the layered GFRP target.

Figure 5 shows the strain fields $\varepsilon_{xx},\%$ at different time steps, after the impact of the target with the projectile. It can be seen from the presented data that immediately at the moment of impact 0...0.13 ms, local deformation occurs at the point of impact and $\varepsilon_{xx}$ reaches values up to 0.8%. Then, at the moments of time 0.13 ... 2.11 ms, the target is involved in the global deformation process, and the areas of maximum deformation move from the center to the periphery.

**Conclusion**

The presented work shows the effect of a protective coating made of polyurea on the ballistic characteristics of specimens based on fiberglass when colliding with a steel projectile in the velocity range of 97...150 m / s. It is shown that an anti-shock coating with a thickness of 1.2 mm and a mass of 0.070 kg is capable of increasing the safe impact speed of a composite plate with dimensions of 200x300x8.5 mm and a mass of 0.93 kg by 19%. Polyurea coating prevents the penetration of the plates due to the ability to exclude the localization of fracture upon impact due to the redistribution of the load [11]. This effect makes it promising to use polyurea coatings for impact protection of laminated composite materials.

The presented experimental data can be used to identify the properties of the numerical model of collision process of steel rigid projectile and layered glass-fibre reinforced polymer target.
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