Hindawi
Advances in Materials Science and Engineering
Volume 2018, Article ID 1264276, 7 pages
https://doi.org/10.1155/2018/1264276

Research Article

Experimental Investigation of Polyurea-Coated Steel Plates at Underwater Explosive Loading

Li-hui Dai, Cheng Wu, Feng-jiang An, and Sha-sha Liao

State Key Laboratory Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

Correspondence should be addressed to Cheng Wu; chengwu@bit.edu.cn

Received 12 October 2017; Accepted 10 December 2017; Published 31 January 2018

Academic Editor: Yuanshi Li

To improve the survivability of ship structures at underwater explosion, thin steel plates coated with polyurea were used to investigate the blast protection effect. During the experimental tests of bare steel plates at different standoff, an appropriate distance was selected as the reference standoff to perform the tests of coated plates. Experimental tests of different coating locations (front versus back) and coating thickness were carried out to study the influencing factors of blast resistance for metal substrate plates. Compared with the bare steel plates, the polyurea coating was found to reduce the deformation of the test plates at blast tests in both cases of the front and back surface locations of the polyurea layer. An increase in the coating thickness also mitigates substantially the deformation of plates. In addition, the properties of the material and the substrate-coating bond strength may also affect the protective effect of the polyurea coating.

1. Introduction

The threat of terrorism in recent years has prompted research into the importance of structural protection of surface ships. On October 12, 2000, the USS Cole was attacked in Aden Harbor, Yemen [1]. The terrorist attack did serious damage on the ship and caused huge economic loss. After the terrorist attack, the importance of materials used to improve the survivability of ships had been focused on.

A series of studies have been carried out to investigate the effect of polymer coatings on different structures when subjected to blast damage or penetration in recent years. The results show that polymer coatings improve the ballistic resistance and explosive resistance of metal structures and buildings [2–8]. When brick wall or concrete structure collapses under the impact of explosive loading, the debris of bricks crush splash. Once the surface of the wall or concrete structure was coated with polyurea, free flying of the fragments of the back face of such structures after blast was prevented [2–4].

Other studies had found that polymeric coating increases the impact resistance of hard substrates, such as metal or composite structure [6–11]. Amini et al. [6] investigated the effect of a polyurea layer casted on the back of a plate under dynamic shock. It was found that polyurea enhanced energy absorption and mitigated the failure of steel plates. Ackland et al. [11] performed experimental and numerical studies of the blast resistance of mild plates coated with polyurea on the back face under local explosive loading. The results showed the residual deformation increase along with the increase in the coating thickness. Besides, Ackland et al. [10, 12] found reduction in deformation of mild steel plates when polyurea coating casted on their back side. Furthermore, they found that the blast resistance effect of a thicker coating on the back surface was superior than that of a thinner one. Roland et al. [8, 9] applied elastomeric coatings on the front face to enhance the ballistic resistance of steel armor under impact loading generated by a high-speed projectile. Furthermore, polymer-metal laminates were also used to improve the ballistic performance, and they provided superior ballistic protection than uniform polyurea coatings.

When applying polymeric material to enhance the blast resistance of the hard substrate, the location of the polyurea layer on the front or back face is important. Influencing factors should be taken into account [12–15].

Ackland et al. [12] applied commercially produced coatings on the surface of mild steel plates to carry out close-in blast experimental tests in air. It was found that the deformation of the steel plate coated with polyurea on the front face was even larger than that of the bare steel plate. However the polyurea coated on the back face effectively reduced the deformation of the plate at blast tests. This proved that the polyurea layer coated on the back face of the mild plate was more effective in increasing the blast resistance effect than that applied on the front face. Amini et al. [13–15] investigated the effect of the polyurea coating on the front and back faces of steel plates. When the coating was sprayed on the front face of the circular steel plate, the compression of the polyurea under the shock loading increased its stiffness, resulting in a better impedance match with the steel plate. Thus, the coating on the loading face of a plate transfers more energy to the plate promoting the failure of steel plates. Contrary to that, the coating deposited on the back face of steel captures and dissipates some energy of initial shock loading impacted on the steel plate. That resulted in reducing the deformation and avoiding plate fracture.

According to the results of researchers above, polyurea coatings could be considered to reduce the vulnerability of ship structures subjected to underwater blast loading.

In this paper, a series of underwater near-field explosion tests were carried out to investigate the effect of the polyurea coating on thin steel plates. The research was focused on the questions how the location of polyurea coating with respect to the loading direction and the thickness of polyurea coating affect the blast resistance performance of steel plates. In addition, the dependence of the deformation and failure of test plates on the standoff between the charge and the steel plate also discussed in this paper.

2. Experimental Setup

During the tests of the effects of the coating location (front versus back) and the coating thickness, the final deformations of steel plates coated and uncoated with polyurea were compared as the evaluation criteria after blast tests.

2.1. Test Plate

2.1.1. Materials. A3 grade steel was used as the substrate plates due to its availability; its mechanical properties are presented in Table 1.

Polyurea is readily synthesized from aromatic or aliphatic isocyanates with chemical functionality of oligomeric diamines [16], which could be easily mixed and sprayed onto the surface of a metal like steel. The plates had been prepared by grit blasting to remove the surface metal rust and then covered with an epoxy primer to enhance the adhesion between metal and polyurea. The polyurea was sprayed onto plates, cured at room temperature, and stored at room temperature for at least one week to ensure stability of the material. The polyurea samples used in this experiment were provided by Qingdao Shamu International Trade Co. Ltd, China. The physical and mechanical properties of the polyurea are listed in Table 2, and the stress-strain characteristics of the polyurea under high strain rates are plotted in Figure 1.

Table 1: Mechanical properties of steel used in blast tests.

Steel	Yield strength (MPa)	Tensile strength (MPa)
A3	235	375–450

Table 2: Physical and mechanical properties of polyurea used in blast tests.

Sample	Tensile strength (MPa)	Fracture elongation (%)
Polyurea	18.1	184

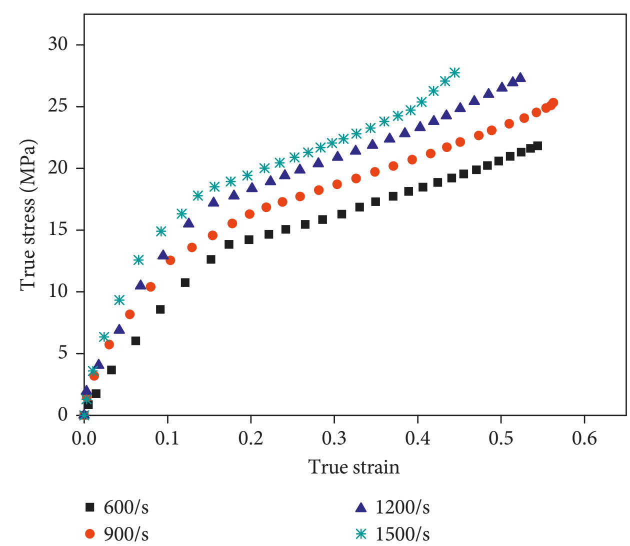


Figure 1: The true tensile stress-strain curves of polyurea under different strain rates.

In Figure 1, the tensile deformation process of polyurea contains three deformation characteristics: an initial linear elastic region corresponding to small deformation; a transitional region of the started yielding; and a viscoplasticity region before fracture. The stress-strain behavior of polyurea at high strain rates exhibits nonlinear and rate dependency. It was also investigated by other researchers [17, 18].

2.1.2. Test Plate Preparation. According to the test requirements, the thickness of the coating polyurea layer on the steel plate was equal to or twice more than the thickness of the substrate plate. In the experimental tests, the thickness of the steel plate was 2 mm; thus, the thickness of polyurea coatings was 2 mm and 4 mm.

It should be noted that, due to spray inhomogeneity, the thickness of the polyurea coating was not as precise as the thickness of steel plates. The average value of the thickness at the center of polyurea coating and at its edges was usually considered as the coating thickness. The calculated areal density of the coatings on the test plates is listed in Table 3.

Table 3: Areal density of different types of test plates.

Type no.	Substrate plate	Coating thickness (mm)	Areal density (kg/m^2)
1	2 mm steel	No	15.6
2	2 mm steel	2	17.7
3	2 mm steel	4	19.8

2.2. Test Setup. The experimental tests were carried out in a water pool, and the experimental test site layout is shown in Figure 2. The length and width of the pool was 2 m × 2 m, and the depth of water was 2 m. The experimental test setup was hanged in the center of the pool, and the charge was 1 m below the free water surface.

The test plate was fixed on the test rig with bolts as shown in Figure 3. The dimensions of test plates were 0.5 m × 0.5 m, with a test area of 350 mm × 350 mm used for the experiment. The details of the plates for blast tests and standoff are listed in Table 4. The long steel rods were used to fix charge on the opposite side of the test plate. The wires tied to the long steel rods could be moved to achieve an appropriate distance between the charge and the test plate.

In each blast test, 10 g cylindrical charge of RDX was suspended in front of the center of the plate to reduce the plate boundary effects. An electronic detonator located centrally in the charge was used for ignition.

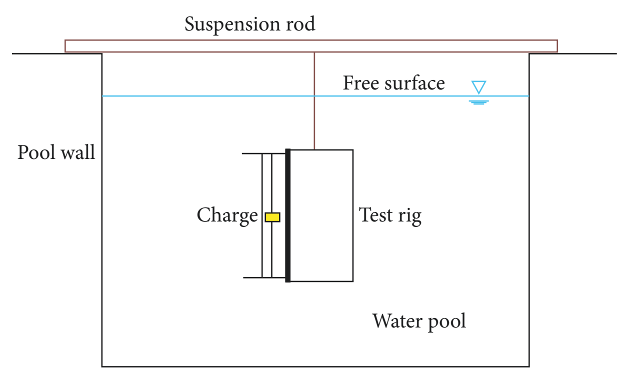


Figure 2: Experimental site layout.

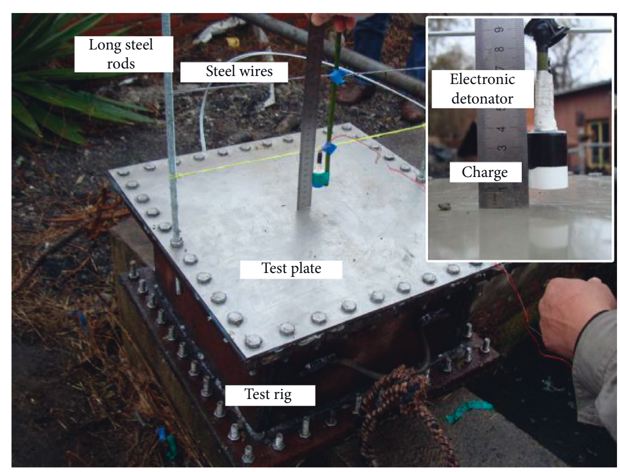


Figure 3: Details of the test setup.

3. Results and Discussion

The tasks of the experimental tests were the effect of the standoff distance, coating location (front versus back), and coating thickness on the substrate deformation. The deformations of the substrates were measured after the test plates unbolted from the test rig.

3.1. Bare Steel Plates at Different Standoff. The deformation and damage of bare steel plates at different standoff are presented in Table 5. In addition, the deformations of each test plate along the width direction are plotted in Figure 4. The maximum deformation of the test plate increased as the distance between the charge and the surface of the test plate decreased, and the local variation in deformation increased obviously.

Once the standoff becomes less, much more energy generated by the charge affected on the test plates, and the degree of test plate deformation increased. The test plates even ruptured, just like test no. 6.

As presented in Figure 5(a), test no. 5, at the 10 mm standoff, the plate did not rupture and just have got dishing deformation. While in test nos. 6 and 7, both at 8 mm standoff the test plates ruptured with a crack or broken into three petals as shown in Figures 5(b) and 5(c), respectively.

According to the results of test no. 6, we assumed that the deformation value at this standoff is the deflection limit for this thickness plate, and it may be considered as a reference value. Thus, the 8 mm gap between the charge and the plate, which was in test no. 6, was determined as the appropriate standoff distance in the subsequent tests.

3.2. Steel Plates Coated with Polyurea. Table 6 shows the deformation test results of the substrate plates with and without polyurea. Besides, the data on relative reduction in deformation of the coated plates with respect to bare plates are also presented in Table 6.

The thick (4 mm) and thin (2 mm) polyurea coatings, whether on the front or back surface of steel plates, reduced about 40% and 30% of the deflection deformation, respectively, while the areal density increased by only 27% or 13%.

The bare steel plates undergo elastic-plastic deformation under explosive loading, and they rupture once the deformation exceeds the ductility limit of the material. The coating mitigates the fracture or reduces the deformation of substrate effectively, regardless of whether it is deposited on the front or rear face. It was also found that once the thickness of polyurea coating increased, the maximum

Table 4: Details of plates for blast tests.

Test no.	Substrate plate	Coating thickness (mm)	Surface	Standoff (mm)
1	2 mm steel	No	N/A	30
2	2 mm steel	No	N/A	20
3	2 mm steel	No	N/A	15
4	2 mm steel	No	N/A	12
5	2 mm steel	No	N/A	10
6	2 mm steel	No	N/A	8
7	2 mm steel	No	N/A	8
B3	2 mm steel	4	Front	8
B4	2 mm steel	4	Back	8
B5	2 mm steel	2	Back	8
B6	2 mm steel	2	Front	8

Table 5: Results of bare steel plates under different standoff.

Test no.	Substrate plate	Standoff (mm)	Maximum deflection (mm)
1	2 mm steel	30	59.0
2	2 mm steel	20	67.4
3	2 mm steel	15	68.1
4	2 mm steel	12	78.6
5	2 mm steel	10	79.7
6	2 mm steel	8	113.5 (a crack)
7	2 mm steel	8	Three petals

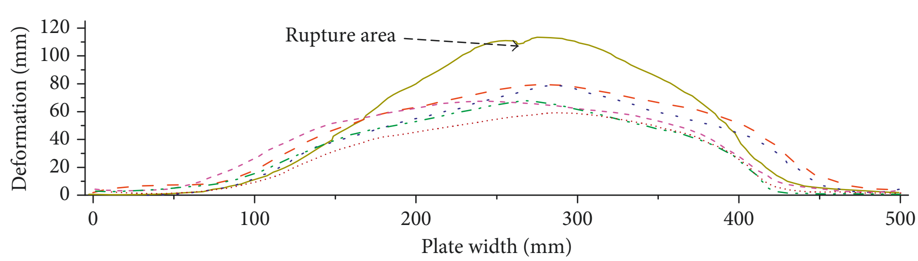


Figure 4: Deformation of bare steel plates after the test along the width direction.

deflection decreased. Therefore, the coating thickness increase is effective for steel plate protection at underwater explosion tests.

As shown in Table 6, in both cases of 2 mm and 4 mm coating thickness, the steel plates with polyurea coated on the front surface performed better than those covered on the rear face at blast tests. The details are discussed below.

3.2.1. Steel Plates with Polyurea Coated on the Front Surface. Figure 6 presents the front faces of two plates coated with different thicknesses of polyurea on the front surfaces. A circular torn hole appeared near the center of each plate. The polyurea coatings disconnected from the steel plate surface and showed a circular debonded area at the center of the plates. The areas surrounded by black dotted lines in Figure 6 are the places where the polyurea layer was totally separated from the plates. The average diameter of the unbonded area was about 260 mm for thin polyurea coating (2 mm), while for thick polyurea coating (4 mm), the value was 210 mm.

The deformation of the steel plate with thin coating (2 mm) was larger than that of the plate coated with thick polyurea (4 mm) as shown in Table 6; thus, the gap between the thin polyurea coating (2 mm) and the steel plate was longer due to the elastic recovery of polyurea. And that may result in a larger debonding area.

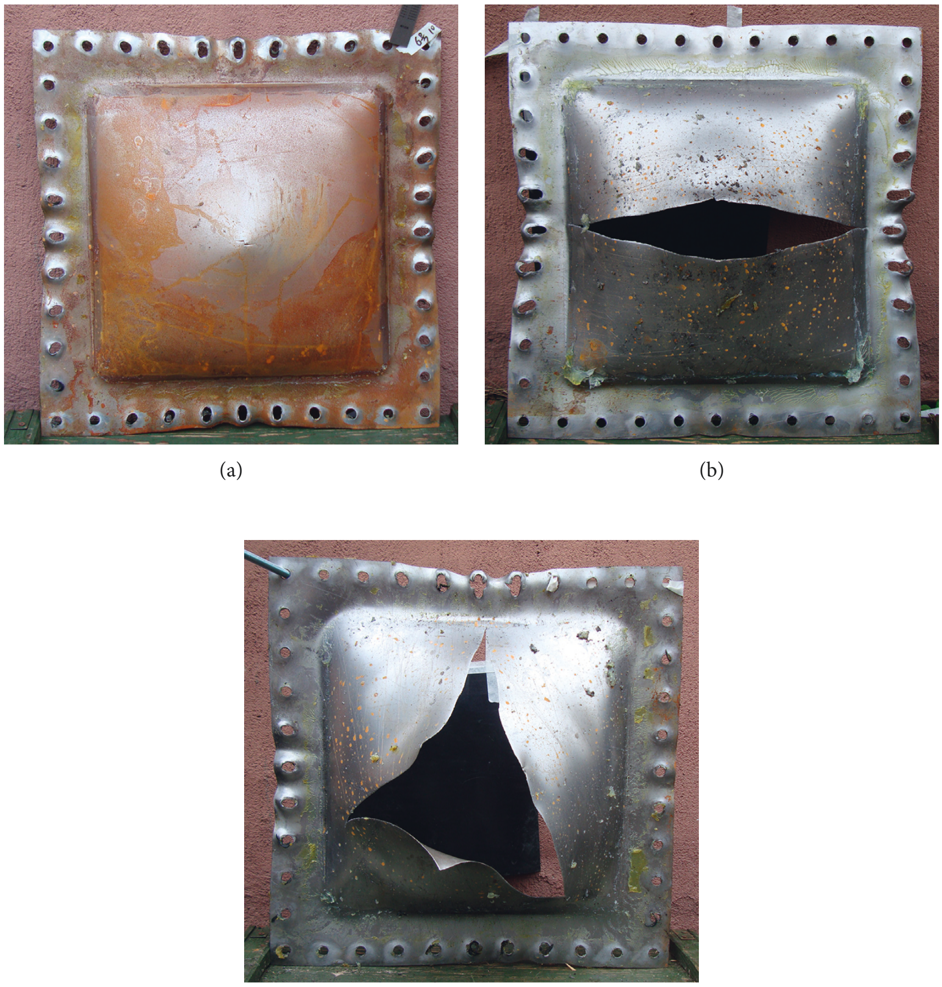


Figure 5: Examples of test plates after test: (a) no rupture (10 mm standoff); (b) a crack (8 mm standoff); (c) three petals (8 mm standoff).

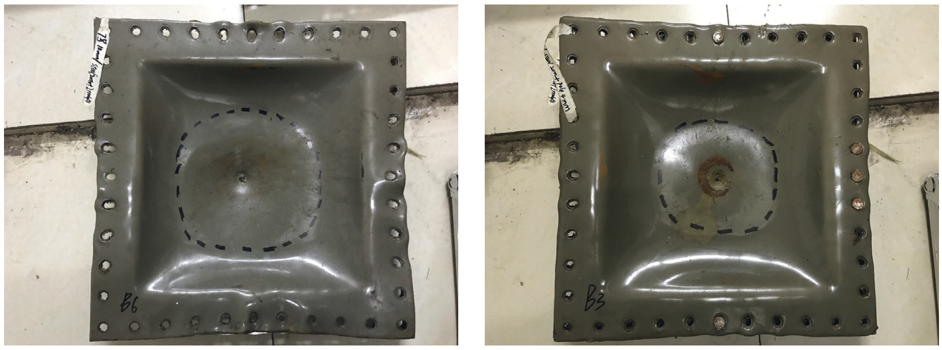
Table 6: Results of test plates coated with polyurea at the same standoff.

Test no.	Coating thickness (mm)	Surface	Maximum deflection (mm)	Areal density increase compared to uncoated plate (%)	Reduction in deformation (%)
6	No	N/A	113.5	—	—
B3	4	Front	66.6	127	41.3
B4	4	Back	68.4	127	39.7
B5	2	Back	81.9	113	27.8
B6	2	Front	78.8	113	30.5

The standoff distance was 8 mm, and the substrate was 2 mm steel plate in each test.

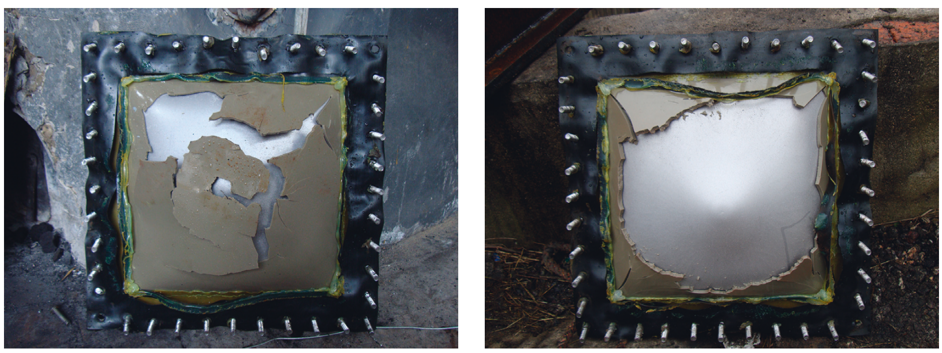
3.2.2. Steel Plates with Polyurea Coated on the Back Surface. Figure 7 presents the back faces of two test plates coated with polyurea of different thicknesses on the back surface. Unlike the damage of polyurea coated on the front surface of steel plates, the polyurea that covered on the back surface of plates not only separated from the substrate plate but also cracked or even fallen off a large-scale area after the blast test. In particular, 4 mm polyurea layer coating completely broken off from the substrate and broke up into several small fragments. In Figure 7(c), there is a hole in the center of the fragment, which may be caused by the initial shock wave.

In general, the fracture of polymer contains brittle fracture and ductile fracture. The brittle fracture usually occurs at the elastic phase, and the fracture cross section is relative smooth without ductile deformation, as shown in Figure 7, whereas the ductile fracture mainly occurs at the plastic or viscous phase, and the cross section shows coarse with obvious ductile deformation.



(a) (b)

Figure 6: Front faces of steel plates with the polyurea layer on the front surface after tests. (a) 2 mm polyurea coating (~260 mm diameter of unbonded layer). (b) 4 mm polyurea coating (~210 mm diameter of unbonded layer).



(a) (b)

(c)

Figure 7: After the test, pictures of the back faces of steel plates with polyurea sprayed on the back surface: (a) 2 mm polyurea coating; (b) 4 mm polyurea coating; (c) fragments of 4 mm coating.

There were two main reasons for the debonding effect and the large area broken off after blast tests in Figure 7. The first one was that the bonding strength between the polyurea material and the substrate was not very strong. Once the initial shock wave impacted on the polyurea, the polyurea layer would separate from the back of the substrate easily. The second one was that the elongation of the polyurea was limited. Once the polyurea layer delaminates from the bilayer structure, it could not be compressed by the impact loading; thus, its stiffness would not increase. Under high strain rate loading, the polyurea would crack at its elastic deformation stage because of low stiffness.

The above two reasons could also explain why the protective effect of polyurea coated on the back face of the substrate plate was weaker than that of polyurea coated on the front surface, which was different from other researcher's experimental results [12, 13]. If the interface bonding strength was strong enough, the initial shock wave would not pull the polyurea layer off from the back of the substrate. Instead, the compressive wave could increase its stiffness. The polyurea would not crack easily under high strain rate and could capture and dissipate a large amount of blast energy because of its viscoelasticity [19]. In addition, the compressive polyurea layer could also increase the bilayer structure's tangent modulus, delaying the onset of the necking instability [19, 20]; once the polyurea separated from the back of the substrate because of weak interface bonding strength, it would fracture easily and only dissipate a small part of shock loading energy. Thus, a large amount of energy would impact on the substrate, which resulted in a big deformation.

Besides, when the polyurea was sprayed on the loading direction face, the actual distance from the substrate to the charge was larger due to the presence of the polyurea layer. This may be also a reason for the different deformation of substrate plates.

4. Conclusions

Underwater explosion tests were carried out to investigate the protective effect of thin steel plates coated with the polyurea layer. The deformation or rupture of a bare steel plate is sensitive to the standoff distance. Therefore, it was necessary to select a suitable standoff as a reference in the experimental tests. Whether coated on the front or rear face of the plate, polyurea could provide significant blast resistance protection for the steel substrate with just a small areal density increase. Increasing the thickness of the polyurea layer on thin steel plates is helpful in reducing the deformation of the test plates at blast tests.

In addition, it was found that the effect of the front coating on mitigating the deformation of the plate is slightly better than the back coating, which is different from other researcher's experimental results. The bonding strength between the substrate and coating and the material properties of the polyurea under high strain rate may be the main reasons for different experimental results.

More studies should be carried out in future to investigate the influence of these factors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors thank the State Key Laboratory Explosion Science and Technology, Beijing Institute of Technology, for providing the test sites and facilities to carry out the experimental tests.

References

[1] A. J. Brown, *AOE 5315 Naval Ship Vulnerability and Underwater Explosion–Introduction to Survivability OnLine Lecture 1*, Virginia Tech Department of Aerospace and Ocean Engineering, Blacksburg, VA, USA, 2004.

[2] S. N. Raman, T. Ngo, P. Mendis et al., "Elastomeric polymers for retrofitting of reinforced concrete structures against the explosive effects of blast," *Advances in Materials Science and Engineering*, vol. 2012, Article ID 754142, 8 pages, 2012.

[3] X. Huang, G. W. Ma, and J. C. Li, "Damage assessment of reinforced concrete structural elements subjected to blast load," *International Journal of Protective Structures*, vol. 1, no. 1, pp. 103–124, 2010.

[4] J. S. Davidson, J. W. Fisher, M. I. Hammons et al., "Failure mechanisms of polymer-reinforced concrete masonry walls subjected to blast," *Journal of Structural Engineering*, vol. 131, no. 8, pp. 1194–1205, 2005.

[5] C. Chen, D. G. Linzell, E. Alpman et al., "Effectiveness of advanced coating systems for mitigating blast effects on steel components," *WIT Transactions on The Built Environment*, vol. 98, pp. 85–94, 2008.

[6] M. R. Amini, J. B. Isaacs, and S. Nemat-Nasser, "Effect of polyurea on the dynamic response of steel plates," in *Proceedings of the 2006 SEM Annual Conference and Exposition on Experimental and Applied Mechanics*, St. Louis, MO, USA, June 2006.

[7] S. A. Tekalur, A. Shukla, and K. Shivakumar, "Blast resistance of polyurea based layered composite materials," *Composite Structures*, vol. 84, no. 3, pp. 271–281, 2008.

[8] C. M. Roland, D. Fragiadakis, and R. M. Gamache, "Elastomer–steel laminate armor," *Composite Structures*, vol. 92, no. 5, pp. 1059–1064, 2010.

[9] R. M. Gamache, C. B. Giller, G. Montella, D. Fragiadakis, and C. M. Roland, "Elastomer-metal laminate armor," *Materials and Design*, vol. 111, pp. 362–368, 2016.

[10] K. Ackland, C. Anderson, and N. St John, "Polymeric coatings for enhanced protection of structures from the explosive effects of blast," *Recent advances in security technology*, vol. 90, 2007.

[11] K. Ackland, C. Anderson, and T. D. Ngo, "Deformation of polyurea-coated steel plates under localised blast loading," *International Journal of Impact Engineering*, vol. 51, pp. 13–22, 2013.

[12] K. Ackland and N. St John, *Experimental and Numerical Investigations into Polymeric Coatings for Blast Protection*, Defense Science and Technology Organization and Maritime Platforms Division, Melbourne, VIC, Australia, 2011.

[13] M. R. Amini, J. Isaacs, and S. Nemat-Nasser, "Investigation of effect of polyurea on response of steel plates to impulsive loads in direct pressure-pulse experiments," *Mechanics of Materials*, vol. 42, no. 6, pp. 628–639, 2010.

[14] M. R. Amini, A. V. Amirkhizi, and S. Nemat-Nasser, "Numerical modeling of response of monolithic and bilayer plates to impulsive loads," *International Journal of Impact Engineering*, vol. 37, no. 1, pp. 90–102, 2010.

[15] M. R. Amini, J. B. Isaacs, and S. Nemat-Nasser, "Experimental investigation of response of monolithic and bilayer plates to impulsive loads," *International Journal of Impact Engineering*, vol. 37, no. 1, pp. 82–89, 2010.

[16] D. Fragiadakis, R. Gamache, R. B. Bogoslovov et al., "Segmental dynamics of polyurea: effect of stoichiometry," *Polymer*, vol. 51, no. 1, pp. 178–184, 2010.

[17] S. N. Raman, T. Ngo, J. Lu et al., "Experimental investigation on the tensile behavior of polyurea at high strain rates," *Materials and Design*, vol. 50, no. 17, pp. 124–129, 2013.

[18] C. M. Roland, J. N. Twigg, Y. Vu, and P. H. Mott, "High strain rate mechanical behavior of polyurea," *Polymer*, vol. 48, no. 2, pp. 574–578, 2007.

[19] M. R. Amini, "Effect of polyurea on dynamic response and fracture resistance of steel plates under impulsive loads," University of California, San Diego, CA, USA, Dissertations & Theses–Gradworks, 2007.

[20] Z. Xue and J. W. Hutchinson, "Neck development in metal/elastomer bilayers under dynamic stretchings," *International Journal of Solids and Structures*, vol. 45, no. 13, pp. 3769–3778, 2008.