Check for updates

Proceedings of the 2019 Hypervelocity Impact Symposium
HVIS2019
April 14-19, 2019, Destin, FL, USA
HVIS2019-095

Study on the explosion-proof performance of polyurea-reinforced masonry walls with different spraying methods

Wei Shang[a], Xu-dong Zu[a], Zheng-xiang Huang[a,*], Wen-ni Shen[a]

[a]*School of Mechanical Engineering, Nanjing University of Science and Technology, Xiao lingwei 200, Nanjing 210094, PR China*

Abstract

Based on the propagation theory of blast waves and the strain rate effect of polyurea, the explosion-proof performance of polyurea-reinforced masonry walls with different spraying methods is discussed in this paper. The impact fracture of masonry walls after contact explosion was analyzed, and the fracture results of a blast wave on polyurea-reinforced masonry walls with different spraying methods were predicted. Furthermore, explosion-proof experiments of a standard masonry wall (2m×1.2m×0.37m) under three conditions including non-sprayed, back surface sprayed polyurea and double-sided sprayed polyurea were carried out to verify the theoretical predictions. Finally, the impact fracture results of standard masonry walls after a 1 kg TNT contact explosion under the three conditions were obtained. The test results were in good agreement with the theoretical predictions. It clearly demonstrated that polyurea coating can significantly improve the explosion-proof performance of masonry walls, and double-sided sprayed showed better explosion-proof performance than back surface sprayed at the same coating thickness.

Keywords: Polyurea; Masonry walls; Impact fracture; Explosion-proof performance

Nomenclature

p_c	compressive stress of the compressional wave (Mpa)
p_t	Tensile stress of the expansion wave (Mpa)
σ_{cmax}	ultimate compressive strength of the wall (Mpa)
σ_{tmax}	ultimate tensile strength of the wall (Mpa)
ρ_0	initial density of the wall (Kg/m^3)
ρ_1	density of the wall after compressional wave (Kg/m^3)
ρ_2	density of the wall after expansion wave (Kg/m^3)
vs, vp	shock-velocity and particle-velocity (m/s)
C	the intercept of the (vp) curve (m/s)
E_0	initial internal energy of the wall (KJ)
E_1	internal energy of the wall after compressional wave (KJ)
γ_0	the unit less Gruneisen gamma
a	first order volume correction to γ_0
S_1, S_1, S_1	unit less coefficients of the slope of the $vs(vp)$ curve
σ_0	tensile yield stress of polyurea under quasi-static condition (Mpa)
σ_y	dynamic tensile yield stress of polyurea (Mpa)
$\dot{\varepsilon}$	strain rate (s^{-1})
DIF	stress enhancement factor
A,B	fitting parameters of the experiment

* Corresponding author. Tel.: +86-18061888202
E-mail address: huangyu@mail.njust.edu.cn.

Downloaded from http://asmedigitalcollection.asme.org/hvis/proceedings-pdf/HVIS2019/883556/V001T07A012/6551153/v001t07a012-hvis2019-095.pdf by guest on 25 September 2022

1. Introduction

In the contemporary world, the frequent occurrence of terrorist incidents has brought a great challenge to building protection. At present, most walls of existing buildings were designed as a masonry structure or reinforced concrete structure. A blast wave will cause damage to the walls and form a large spalling area on the back of the walls which seriously threatens the safety of personnel and equipment inside the walls. Therefore, it becomes an urgent matter to carry out research on enhancing explosion-proof performance of walls under the premise of guaranteeing the existing building structure unchanged. Experimental and simulation studies found that [1] polymer coating can enhance the explosion-proof performance of existing walls, which made the explosion shock response characteristics of sprayed polymer-reinforced walls a research hotspot.

Polyurea is a green polymer coating with excellent impact and tear resistance. It has great potential in the field of anti-terrorism and explosion protection. After spraying it on the surface of walls, polyurea can absorb blast wave energy and reduce secondary injury caused by wall spalling during the explosion process [2-3]. Over the past decade, much research has been done on the dynamic mechanical properties of polyurea and the impact response characteristics of walls. Jongmin Shim [4] and S.N. Raman [5] tested the tensile and compression dynamic performance of polyurea over the strain rate region from 10^{-2} to 10^{4}/s. Results showed that the stress–strain behavior of polyurea at high strain rates is considerably non-linear and exhibits significant strain rate sensitivity. Hui Guo et al. [6] developed a three-dimensional visco-hyperelastic constitutive model to describe the finite deformation mechanical behavior of polyurea materials at different strain rates, and carried out nonlinear stress-strain behavior experiments of polyurea under uniaxial tension and compression to validate the effectiveness of the constitutive model. Jun Li et al. [7] investigated spall damage of generic reinforced concrete columns subjected to blast loads numerically. Kai X et al. [8] carried out a numerical simulation study on the concrete spallation under various blast loading and structural conditions and established the spallation criteria for different levels of spallation. Lee G. Moradi et al. [9] studied the resistance of membrane retrofitted concrete masonry walls to lateral pressure. Sanam Aghdamy et al. [10] developed numerical models to simulate the response of concrete masonry unit walls retrofitted with polyurea coating and proved that the sprayed polyurea improved the explosion resistance of walls. James S. Davidson et al. [11-12] carried out failure mechanisms and experimental testing investigations of polyurea-reinforced concrete masonry walls subjected to blast loading. Results showed that the explosion-proof performance of a masonry wall can be significantly enhanced by spraying polymer on the walls. The above research only showed that the sprayed polyurea wall has a good explosion-proof performance, however, there is a lack of in-depth analysis on its explosion-proof mechanism and spraying method.

Based on the propagation theory of blast waves and the strain rate effect of polyurea, this paper analyzes the impact fracture of masonry walls under the blast wave of a contact explosion and predicts the impact fracture results of a blast wave on polyurea-reinforced masonry walls with different spraying methods. At the same time, explosion-proof experiments of standard masonry walls (2m×1.2m×0.37m) under three conditions were carried out to verify the theoretical predictions.

2. Impact fracture analysis of walls under blast loading

For a non-sprayed wall, detonation products with high temperature and high pressure characteristics have a strong impact on the wall. Because the rate of heat conduction is much less than that of a blast wave, the effect of temperature increase on the explosion-proof performance of the wall is ignored [13]. Therefore, research on the explosion-proof mechanism of a polyurea-reinforced wall should start from propagation of the shock wave. According to the impedance effect of the medium, a blast wave will exhibit multiple reflections at the interface of the wall. At the initial moment of detonation, due to the fact that the impact impedance of the wall is greater than that of the explosive, compressive stress generates a compression wave under blast loading. A pit will appear on the surface of the wall. The Gruneisen equation of state with cubic shock-velocity as a function of particle-velocity (vp) defines pressure p_c for compressed materials as [14]

$$p_c = \frac{\rho_0 C^2 \mu_1\left[1+\left(1-\frac{\gamma_0}{2}\right)\mu_1-\frac{a}{2}{\mu_1}^2\right]}{\left[1-(S_1-1)\mu_1-S_2\frac{{\mu_1}^2}{\mu_1+1}-S_3\frac{{\mu_1}^3}{(\mu_1+1)^2}\right]}+(\gamma_0+a\mu_1)E_0 \quad (1)$$

where ρ_0 is the initial density of the wall, ρ_1 is the density of the wall after compression, C is the intercept of the (vp) curve (in velocity units), S_1, S_2, and S_3 are the unit-less coefficients of the slope of the $vs(vp)$ curve, γ_0 is the unit-less Gruneisen gamma, a is the unit-less first order volume correction to γ_0, $\mu_1 = \rho_1/\rho_0 - 1$, and E_0 is the initial internal energy of the wall.

Downloaded from http://asmedigitalcollection.asme.org/hvis/proceedings-pdf/HVIS2019/883556/V001T07A012/6551153/v001t07a012-hvis2019-095.pdf by guest on 25 September 2022

If the shock wave strength is greater than the ultimate compressive strength of the wall， the wall will be crushed. σ_{cmax} is the ultimate compressive strength of the wall.

$$\frac{p_c}{\sigma_{cmax}} \geq 1 \tag{2}$$

When the shock wave propagates to the back of the wall due to the impact impedance of air being much smaller than that of the wall, a tensile stress is generated due to the influence of the expansion wave, and a bulge appears on the wall. The tensile stress p_t is defined as

$$p_t = \rho_1 C^2 \mu_2 + (\gamma_0 + a\mu_2)E_1 \tag{3}$$

In equation (3), $\mu_2 = \rho_2/\rho_1 - 1$, ρ_2 is the density of the wall after the expansion wave, and E_1 is the internal energy of the wall after the compressional wave.

When the reflected expansion wave propagates to the front of the wall, the crushed wall will be thrown outward which will further enlarge the crater of the wall.

If the shock wave strength is greater than the ultimate tensile strength of the wall during this process, it will generate spallation where σ_{tmax} is the ultimate tensile strength of the wall.

$$\frac{p_t}{\sigma_{tmax}} \geq 1 \tag{4}$$

The expansion wave is reflected back and forth at the interface between the wall and air, until the wave energy inside the wall is completely attenuated. At this moment, maximum fracture occurs [15].

From the above analysis, when the blast wave impacts on the non-sprayed wall, obvious fractures appear or even cause collapsing on both sides of the wall. Fig. 1 shows the process of a blast wave impacting on the non-sprayed wall.

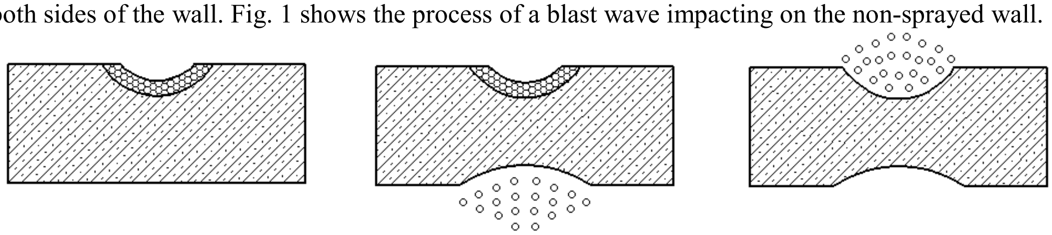


Fig.1. Impact process of a blast wave on the non-sprayed wall (a) Front surface of the wall is crushed after the compressional wave. (b) Back surface of the wall generates spallation after the expansion wave. (c) The crushed wall is thrown outward after the reflected wave.

For composite walls, the ultimate tensile and compressive strengths are determined by the component of the maximum ultimate tensile and compressive strengths [16]. Polyurea is a strain rate sensitive material. S.N. Raman et al. [5] found that the relationship between tensile yield stress of polyurea σ_y , the stress enhancement factor DIF, and the strain rate $\dot{\varepsilon}$ can be well described by equations (5) and (6).

$$\mathrm{DIF} = \mathrm{A}\ln(\dot{\varepsilon}) + B \tag{5}$$

$$\sigma_y = DIF \times \sigma_0 \tag{6}$$

where σ_0 is the tensile yield stress of polyurea under quasi-static conditions, and A and B are fitting parameters of the experiment. S.N. Raman et al. gave the fitting results shown in Table 1. Research has shown [17] the strain rate of solid materials under explosive load is about 10^4/s~10^6/s. Therefore, the dynamic tensile yield stress of polyurea is up to 3.5~5.0 times larger than that under quasi-static conditions.

Downloaded from http://asmedigitalcollection.asme.org/hvis/proceedings-pdf/HVIS2019/883556/V001T07A012/6551153/v001t07a012-hvis2019-095.pdf by guest on 25 September 2022

According to strain rate effect analysis, the dynamic tensile strength of polyurea under explosive load is much larger than the dynamic tensile strength of the wall [18]. It predicts that the back surface of a sprayed wall will not exhibit a large area collapse under the protection of the polyurea coating, while the front side of the wall will be seriously damaged. For the double-sided sprayed wall, both the front and the back surfaces are protected well by a polyurea coating. The overall fracture area is much smaller.

Table 1. Coefficients A and B for DIF of yield stress at different ranges of strain rates

Strain rate range	A	B
$\dot{\varepsilon} < 10^{-2}$	0.0068	1.0572
$10^{-2} \leq \dot{\varepsilon} < 10^{2}$	0.1043	1.5065
$\dot{\varepsilon} \geq 10^{2}$	0.3347	0.4422

3. Explosion-proof experiments of walls

In order to verify the impact fracture results of a blast wave on a polyurea-reinforced wall with different spraying methods, explosion-proof experiments of standard masonry walls were carried out to study the deformation and fracture of the walls. The thickness of the masonry walls is 0.37m, which is a widely used thickness in Chinese buildings. Figs. 2 and 3 respectively show the structural dimensions of standard masonry and the experimental setup. The explosives used in these experiments were TNT columns (see Fig.4) detonated with an 8# fire detonator. The back-surface sprayed wall had uniformly sprayed polyurea on the back surface of the masonry wall, and the thickness of the coating was 10mm. The double-sided sprayed wall had polyurea sprayed on both sides of the masonry wall. The thicknesses of the coatings were 3mm on the front surface and 7mm on the back surface. The numbers of non-sprayed, back-surface polyurea sprayed and double-sided polyurea sprayed masonry walls were # 1, # 2 and # 3.

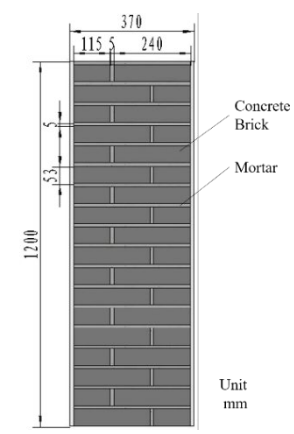


Fig 2. Structural dimensions of standard masonry walls

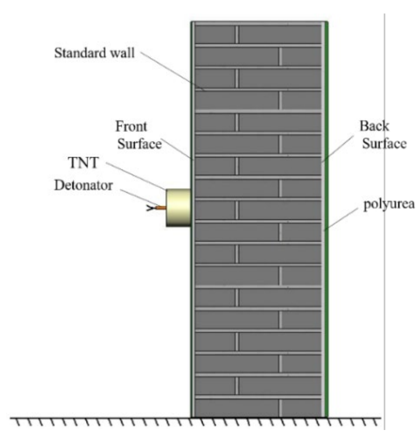


Fig 3. Experimental setup

Downloaded from http://asmedigitalcollection.asme.org/hvis/proceedings-pdf/HVIS2019/883556/V001T07A012/6551153/v001t07a012-hvis2019-095.pdf by guest on 25 September 2022

Fig 4. Physical map of TNT column

4. Experimental results and analysis

Fig. 5 shows the impact fracture results of a non-sprayed masonry wall after a 1 Kg TNT contact explosion. A large hole with a diameter of 900mm appeared and large cracks diffused around the explosion center. Because there were no constraints, the top side of the wall formed a gap 1400 mm in length. The masonry wall is left perforated and the overall damage is significant.

Fig 5. Impact fracture of non-sprayed masonry walls on the front surface

Fig. 6 shows the impact fracture of the masonry wall sprayed with 10mm polyurea on the back surface after a 1 Kg TNT contact explosion. It can be seen that the fracture of the front surface of the wall is similar to that of the non-sprayed masonry wall with large holes and cracks. But the aperture and cracks are greatly reduced compared with those of the non-sprayed masonry wall. The aperture is 520 mm, which is 42.2% less than that of the non-sprayed masonry wall. Moreover, there is only a 68 mm thick bulge appearing on the back surface of the wall and no collapsing or cracks occurred on the back surface due to the protection of the polyurea coating. The wall is not completely perforated, and the depth of the hole is 245 mm which is 33.8% less than that of perforation. There is no obvious gap appearing on the top side of the wall. Experimental results show that the impact fracture under a blast wave can be effectively reduced by spraying polyurea on the back surface of the wall.

（a）

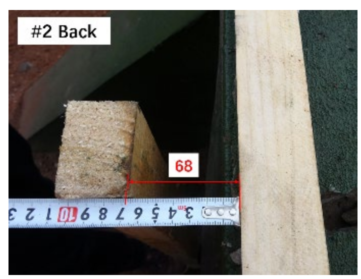
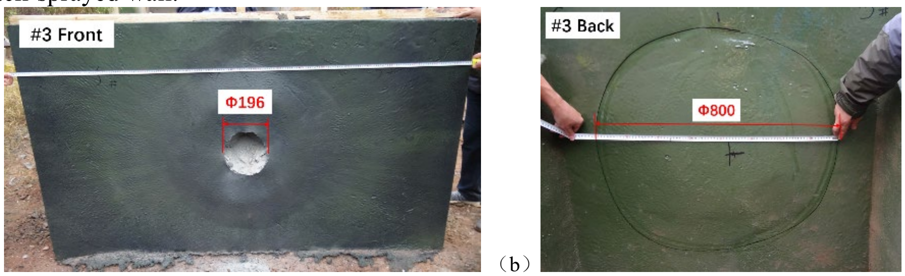

（b）


Fig 6. Impact fracture of back surface sprayed polyurea masonry walls (a) Front surface ; (b) Back surface

Fig. 7 shows the impact fracture of the masonry wall with 3 mm of polyurea sprayed on the front surface and 7 mm of polyurea sprayed on the back surface after a 1 Kg TNT contact explosion. On the front surface of the masonry wall, there is a hole of only 196 mm in diameter. The aperture is 78.2% smaller than that of the non-sprayed cases. There is also no obvious fracture on the back surface of the wall, which only exhibits a bulge with diameter of 800 mm and thickness of 38 mm. The thickness of the bulge decreases by 44.1% compared with the back-surface polyurea sprayed masonry wall. There are no obvious cracks on both sides of the wall. In addition, the wall is not completely perforated, and the depth of the hole is 72 mm which is 80.5% less than that of perforation. There is almost no fracturing on the top side of the wall. However, it is noteworthy that there are obvious bulges on the front surface of the wall, and the inner wall of the bulging area is severely broken. Experimental results show that when the blast wave is reflected back and forth in the wall, the bricks inside the wall are crushed in a large area and the energy of the shock wave is consumed, while the surface of the wall is damaged less due to the protection of the polyurea coating. Therefore, the explosion-proof performance of a double-sided sprayed masonry wall is better than that of a back-side sprayed wall when the thickness of the polyurea coating is kept unchanged.

Downloaded from http://asmedigitalcollection.asme.org/hvis/proceedings-pdf/HVIS2019/883556/V001T07A012/6551153/v001t07a012-hvis2019-095.pdf by guest on 25 September 2022

According to the analysis of the experimental results, the deformation and fracture of the wall under three different working conditions are shown in Table 2. It can be concluded that a polyurea coating can greatly improve the explosion-proof performance of masonry walls, and when the thickness of the coating is a constant, the explosion-proof effect of a double-sided sprayed wall is better than that of a back-sprayed wall.



（a）（b）

Fig 7. Impact fracture of double-sided polyurea sprayed masonry wall (a) Front surface ; (b) Back surface

Table 2 Anti-explosion experimental results of concrete masonry walls

Wall	Component description	Failure characterization
#1	Standard masonry wall	Control wall severely fragments and collapses. Large holes and cracks appear in the wall. The diameter of centre hole is 900mm. The length of the gap on the top side of the wall is 1400 mm. The wall is perforated.
#2	Standard masonry wall+ 10 mm thick polyurea coating on the back surface	The front surface of the wall is severely overloaded. Holes and cracks appear on the front surface. The diameter and depth of the hole are 520mm and 245mm. A bulge but no cracks appear on the back surface. The thickness of the bulge is 68mm. The wall is not completely perforated.
#3	3 mm thick polyurea coating on the back surface +Standard masonry wall+ 7 mm thick polyurea coating on the back surface	A small hole and no cracks appear on the front surface. The diameter and depth of the hole are 196mm and 72mm . A bulge and no cracks appear on the back surface of the wall. The diameter and thickness of bulge are 80mm and 38mm. The wall is completely perforated.

5. Conclusion

Based on the propagation theory of blast waves and the strain rate effect of polyurea, the impact fracture of sprayed polyurea reinforced walls under blast loading are predicted. Explosion-proof experiments of masonry walls were carried out to verify the predicted results. The following conclusions are obtained:

(1) Sprayed polyurea reduces the tensile fracture of masonry walls caused by an expansion wave. Thus, it reduces the gaps and cracks of the wall under a blast wave, significantly improving the explosion-proof performance of the wall.

(2) When the thickness of the polyurea coating is the same, the deformation and damage of a double-sided sprayed masonry wall is much smaller than that of a back-surface sprayed wall. Therefore the explosion-proof performance of a double-sided sprayed wall is better.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Grant No. 11872214).

References

[1] Buchan P A, Chen J F. 2007, Blast resistance of FRP composites and polymer strengthened concrete and masonry structures – A state-of-the-art review. Composites Part B: Engineering. 38(5-6): 509-522.

[2] Y.A. Bahei El Din, G.J. Dvorak, O.J. Fredricksen. 2006, A blast-tolerant sandwich plate design with a polyurea interlayer. Int. J. Solids Struct. 43:7644–7658.

[3] S.A. Tekalur, A. Shukla, K. Shivakumar. 2008, Blast resistance of polyurea based layered composite materials. Compos. Struct. 84:271–281.

Downloaded from http://asmedigitalcollection.asme.org/hvis/proceedings-pdf/HVIS2019/883556/V001T07A012/6551153/v001t07a012-hvis2019-095.pdf by guest on 25 September 2022

[4] Shim J, Mohr D. 2009, Using split Hopkinson pressure bars to perform large strain compression tests on polyurea at low, intermediate and high strain rates. International Journal of Impact Engineering. 36(9): 1116-1127.
[5] Raman S N, Ngo T, Lu J, et al. 2013, Experimental investigation on the tensile behavior of polyurea at high strain rates. Materials & Design. 50: 124-129.
[6] Guo H, Guo W, Amirkhizi A V. 2017, Constitutive modeling of the tensile and compressive deformation behavior of polyurea over a wide range of strain rates. Construction and Building Materials. 150: 851-859.
[7] Li J, Hao H. 2014, Numerical study of concrete spall damage to blast loads. International Journal of Impact Engineering. 68: 41-55.
[8] Xu K, Lu Y. 2006, Numerical simulation study of spallation in reinforced concrete plates subjected to blast loading. Computers & Structures. 84(5-6): 431-438.
[9] L.G. Moradi, J.S. Davidson, R.J. Dinan. 2008, Resistance of membrane retrofit concrete masonry walls to lateral pressure. Perform Constr Facil, 22 (3): 131-142.
[10] Aghdamy S, Wu C, Griffith M. 2013, Simulation of Retrofitted Unreinforced Concrete Masonry Unit Walls under Blast Loading. International Journal of Protective Structures. 4(1): 21-44.
[11] Dinan R J, Porter J R, Davidson J S, et al. 2005, Failure Mechanisms of Polymer-Reinforced Concrete Masonry Walls Subjected to Blast. Journal of Structural Engineering. 131(8): 1194-1205.
[12] Davidson J S, Porter J R, Dinan R J, et al. 2004, Explosive Testing of Polymer Retrofit Masonry Walls. Journal of Performance of Constructed Facilities. 18(2): 100-106.
[13] Ruan Z, Chen L, Fang Q. 2015, Numerical investigation into dynamic responses of RC columns subjected for fire and blast. Journal of Loss Prevention in the Process Industries. 34: 10-21.
[14] LS-DYNA. 2015, LS-DYNA KRYWORDS USER'S MANUAL, LS-DYNA R8.0.
[15] Cullis I G. 2001, Blast waves and how they interact with structures. J R Army Med Corps. 147(1): 16-26.
[16] Sitnikova E, Guan Z W, Schleyer G K, et al. 2014, Modelling of perforation failure in fiber metal laminates subjected to high impulsive blast loading. International Journal of Solids and Structures. 51(18): 3135-3146.
[17] Marc Andr Meyer. 1994. Dynamic behaviors of materials[M].
[18] Habel K, Gauvreau P. 2008, Response of ultra-high performance fiber reinforced concrete (UHPFRC) to impact and static loading. Cement and Concrete Composites. 30(10): 938-946.

Downloaded from http://asmedigitalcollection.asme.org/hvis/proceedings-pdf/HVIS2019/883556/V001T07A012/6551153/v001t07a012-hvis2019-095.pdf by guest on 25 September 2022