Numerical and Experimental Study on the Locally Blast Loaded Polyurea Coated Steel Plates

FLORINA BUCUR, EUGEN TRANA, ADRIAN ROTARIU*

Military Technical Academy Ferdinand I, 39-49 G. Cosbuc Av., Bucharest, Romania

The damages and casualties inflicted by mine and IED attacks in security challenging areas generated a strong and quick response from nations all over the world. As a part of this response several national and private research facilities increased their efforts in identifying and implementing new ways or technologies to enable blast wave mitigation. The current paper aim to investigate the opportunity of using polyurea coated steel plates as a possible new blast mitigation approach, as suggested by several investigators. In order to objectively conclude about the ability of polyurea coated plates to sustain locally blast loads several experimental tests were performed according to STANAG 4569 demands for a 1/6 scaled plate structure. In order to numerically validate the experimental results several Autodyn simulations were set-up. The numerical and experimental results exhibits a fair correlation, both pointing towards a dismiss of the idea of using polyurea coated steel plates as structural and cost effective blast mitigation approach.

Keywords: coated metal plates, polyurea layer, blast load, numerical simulation

Blast loading research for ballistic protection evaluation of structures and the development of blast-proof materials have been in progress over the last decades. The response of multilayer structures of polymer/metal type, subjected to impulsive loads, is one of the studied topics.

The research regarding implementation of polymeric materials in civilian and military application is in full development nowadays, due to their proven superior mechanical properties, viscoelasticity and hyperelasticity and low cost price. A survey in scientific literature emphasizes that the most used and tested technical polymer with significant results is polyurea. By its simple way of deposition, it forms a 100% solid, continuous and waterproof film with no harmful effect on the environment and with high thermal resistance compared to other technical elastomers [1, 2].

The scientific literature contains a series of experimental studies regarding the use of polyurea to improve the existing structures properties, especially to increase the blast and impact proof protection of buildings, vehicles and personnel [3-7].

As long as such structures include materials of highly different mechanical properties, the development of analytical models, based on simplification assumptions, to better understand global response of the structure may provide unsatisfactory results, which implies necessity to develop empirical relations that match the cause (i.e. impulse loading) with the effect (i.e. produced deformation).

An alternative at hand to understand and assess the modification of the complex structures response is numerical approach, where the structure and the adjacent loading medium are discretized and associated with specific constitutive laws [8-10].

The polyurea specific law is obtained through a number of mechanical experiments at low and high deformation rates [11]. These experiments have shown that the polyurea exhibits elastic and almost incompressible behavior and its stress-strain response is largely depending on deformation, temperature and pressure [6]. Experimental studies (uniaxial tension or compression) have been made for a range of strain rate between 10^{-3}

6000 s^{-1} [6]. The most accessible model proposed for the polyurea, valid for a large (wide) range of deformation rates, is a nonlinear viscoelastic model based on two dependent functions: the deformation-dependent function described by the Mooney-Rivlin model, and the time-dependent behavior described by the Prony series [12]. The specific stress-strain curves show a strong strengthening trend, only after the deformation reaches 100% [11], a value unattainable for most of the steels in uniaxial load.

Anyway, for ductile soft metals coated with polyurea, a delay of necking was observed, a prove of its capability to improve the energy absorption and dynamic performance of structures, fact experimentally and numerically demonstrated by test with SHPB and blast tests [13- 15].

Lab tests on small plates uniformly loaded show that at the energy level that produced catastrophic fractures in armor steel, plates coated with polyurea resist without any fracture, even if the mass added is less than 10%, and the polyurea layer is added to the face subjected to blast load [16]. Regarding the position of layer, better results were obtained when polyurea layer was coated on the back side on structure subjected to dynamic or impulsive loads [17].

In a more recent study, reference and coated mild steel plates were exposed to blast load in range tests at the levels that do not produce necking of the plates. Measuring the permanent maximal deflection and using the proposed assessment formulas, there was observed that the effect of polyurea coating on the applying pressure face is strongly dependent on the stand-off, more exactly at lower stand-off distance the polyurea layer proved to be less effective [18].

The current paper aims to analyse the behavior of steel/polyurea plates by experimental and numerical tests.

The experimental program consists of small scale blast loads tests on reference and polyurea coated plates (on one of the sides) with explosive charge in close proximity of the plates. The organization and the tests conducting, the experimental measurements and post-test evaluation of the results are presented gradually.

Furthermore, we analyse the effect of elastomer coats on the impulsive behavior of the steel plates in the bilayer configuration by numerical means, namely by building

* email: adrian.rotariu@mta.ro

virtual models in AUTODYN®. Several specific aspects that affect the numerical model accuracy, like test rig and plates discretisation solution, polyurea constitutive model, REMAP techniques, Euler/Lagrange interaction, and gauge definitions are addressed.

In discussion section, the efficacy of the polyurea layer is assessed through relevant formulas and a comparison between experimental and numerical results.

Experimental part

Materials and experimental set-up

The experimental tests were conducted in an open army shooting range on a small-scale test rig in order to evaluate the effects of an additional polyurea layer on the local and global behavior of a metal structure that simulate a vehicle belly subjected to a mine blast. The final dimensions for studied configuration resulted from the scaling process (1/6 scale) are 1000 mm x 200 mm for plate dimensions and a total mass of 50.85 kg for test rig.

Three types of plates were tested: 2 mm thickness bare plates as reference and coated plates on inside or outside. For the steel plates an **OL50** steel with 342 N/mm² yield stress, 21% fracture elongation and 7.81 g/cm³ density was used. This relatively soft steel with small yield tension value was chosen to ensure a larger deflection of metal plates. For the polymer layer a quantity of 400 g polyurea was sprayed on each side of steel plate. A 1.1 g/cm³ density polyurea layer (EUROPOL®) with 2 mm thickness and 180 mm width was used. Two lateral narrow bands of 10 mm, close to the bent edges of plates, remained uncovered by polyurea (Fig. 2b). The plates were attached to the reusable rig by two lateral rows of fasteners. The polymer layer brings an areal density increase of 12.67%.

As explosive charges, cylindrical blocks of 30 g of C4 plastic explosive were prepared. The charge quantity was calculated based on the scaling law, and replaces the surrogate charge of 8 kg TNT (level III [19]). The scaled reusable steel pot with the explosive charge encapsulated in a polystyrene shell was placed on the soil

surface under the structure center, at a scaled ground clearance of 141.6 mm (Fig. 1). The charge detonation was initiated by an electrical detonating blast cap inserted in charge through the steel pot central hole.

The test rig was accessorised in order to record overpressure, acceleration and transmitted pulse to structure. For test recording, a measure chain was used: a pressure transducer (PCB 102B06) mounted in a face-on position (the sensitive transducer surface is positioned parallel to the blast wave front for the measurement of overpressure that is transmitted behind the witness plate), a second pressure transducer (PCB 102B04) mounted in a side-on position above the center of the plate and an accelerometer (PCB 350B21) mounted on the test rig edge in the center on the lateral side.

For recording the experimental tests, a PHOTRON high speed camera located at a 15 m distance from the test site and an acquisition data system, PicoScope® 6, were used.

All data recorded and saved through the acquisition software, were analyzed and processed. The experimental test set-up overview is depicted in figure 1.

A number of seven tests were performed as follow: three tests for witness-plate (reference plate), two tests on bilayer plate with back coated polyurea (opposite side of plate) and two tests on bilayer plate with front coated polyurea (in direct contact with the explosion front). Data acquired by accelerometer and pressure transducer were recorded to be analyzed and further processed. Each channel had independent trigger. Acceleration signals were processed using Mathcad software. The evolution of the structure ascending velocity by integrating acceleration signals was calculated. Each performed test was recorded with high speed camera.

After performing the tests, it was analyzed in which manner the plates were affected by the impulse transferred to structure. All tested plates presented deflection with a dishing pattern in central area, right above the charge. When polyurea layer was directly exposed to detonation

Fig. 1. Experimental set-up

Fig. 2. Typical example of experimental data resulted from bilayer plate testing- back coated polyurea

gases, a deterioration of the polyurea layer in the central area was observed. For each tested plate the maximum permanent deflection was measured. The impulse transmitted to rig was evaluated by meaning of images captured by high speed camera. The measurements results and calculated data are presented in table 2. Typical example of experimental data resulted from bilayer plate testing are shown in figure 2.

Numerical modeling

A further analysis of the interaction and effects of shock waves on experimentally tested structures was conducted using AUTODYN®, a numerical modeling software.

The numerical approach consist in two steps. An initial axial 2D model was build only with the steel pot (Lagrange part) and the explosive charge and the surrounding air (Euler part). Such model, having a reduce number of elements of small dimensions, was able to reproduce with high fidelity the charge detonation and the shock wave propagation through air till the moment just before of the shock wave/structure interaction. According to standard procedure, the charge was bottom initiated. For the explosive charge an JWL (Jones-Wilkins-Lee) equation of state was used.

The shock wave/structure interaction imposes an 3D model. For the 3D model, a EULER space was defined and loaded with air at normal atmospheric pressure. An uniform

meshing technique for the 140 x 400 x 600 mm³ volume was used.

For the all metallic rig components the shell meshing option was choosed. The thickness for each component was defined according to the real dimensions. For the test plates uniform size quad elements of 5 mm x 5 mm were used. Following the meshing procedure, 16,000 elements were resulted. The polyurea layer was modeled as Lagrange part with volume elements as long as the hyperelastic materials can not be associated with shell elements. For the meshing of the 2 x 180 x 1000 mm³ polyurea layer a total of 14,400 volume elements were created. The nodes joint option was used in order to model the polyurea layer attachment to the metallic plates. In a similar manner all the test rig components were joined together to behave as a single body.

On the plate and test bench, five virtual transducers were placed as shown in figure 3: two for measuring the velocity induced to plate by the shock wave (2, 4), two for measuring the overpressure (3, 5) and one transducer in plate for measuring the von Mises stress (1).

The material models used for the explosive, air, metallic plates, polyurea layer and rig components are presented in table 1.

AUTODYN® solver does not allow the input of the polyurea model parameters with Prony series experimentaly determined by Gamonpilas and Mccuiston

Fig. 3.
Experimental
set-up and
transducers
location for
standard plate
testing

Material name	AIR	C4	STEEL 4340	OL 50	POLYRUBBER
Reference Density(g/cm ³)	0.001225	1.601	7.83	7.81	1.1
Equation of state	Ideal Gas	JWL	Liniar	Liniar	Hyperelastic
Gamma	1.4				
Reference Temperature(K)	288.200012		300	293	293
Specific Heat(J/kgK)	717.599976		476.99		
Parameters					
	A (kPa)	6.0977·10 ⁸			
	B (kPa)	1.295·10 ⁷			
	R1	4.5			
	R2	1.4			
	W	0.25			
C-J Detonation Velocity (m/s)		8.193·10 ³			
C-J Energy (kJ/m ²)		9.000001·10 ⁸			
C-J Pressure (kPa)		2.8·10 ⁷			
Bulk Modulus (kPa)			1.59·10 ⁸	1.75·10 ⁸	
Strength Materials					
Constitutive Model			Johnson Cook	Johnson Cook	Hyperelastic Mooney-Rivlin
Parameters(kPa)	C10				-4.2427·10 ⁴
	C01				6.1849·10 ⁴
	C11				-1.777·10 ³
	C20				257
	C02				1.4578·10 ⁴
Shear Modulus (kPa)			8.18·10 ⁷	8.08·10 ⁷	
Yield Stress (kPa)			7.92·10 ³	3.42·10 ³	
Hardening constant (kPa)			5.1·10 ³	3.005·10 ³	
Hardening Exponent			0.26	0.24	
Strain rate constant			0.014	0.022	
Thermal Softening Exponent			1.03	1	
Melting Temperature (K)			1.793·10 ³	1.811·10 ³	
Reference Strain Rate			1	1	

Table 1
MATERIAL MODELS
FROM AUTODYN®
LIBRARY [20]

[1]. Due to this shortcome the coefficients of Mooney-Rivlin model were determined for a mean value of strain rate of 200 s^{-1} .

The final step of the 3D model building consisted in data importing on Euler space from the axial 2D model at time $t = 0.0289 \text{ ms}$ through the REMAP option.

40 ms time spam for each simulation was set-up [21].

For the numerical simulation of the front coated polyurea plate subjected to blast load a problem of interaction has occurred between air defined as an Euler environment and polyurea layer of Lagrange type with elements of volume type.

If in the simulation of back coated polyurea, the interaction takes place between Euler elements and Lagrange shell elements, in the case of front coated polyurea, the interaction occurs between Euler elements and Lagrange volume elements.

For this simulation the results are significantly different from the other two test types simulated (reference plate and back coated polyurea plate) and the experiment. The impulse transferred to the structure increases with 75 %.

To eliminate the inconvenience of an unjustified increased momentum, we chose to cover the Lagrange discretization corresponding to the polyurea layer with a shell discretization of thickness and consistency of an aluminium 0.01 mm thickness foil shown in figure 4. At this thickness the foil has a negligible mass and do not affect the impulse transfer from the shock wave to the structure. For the aluminum model, the AL5083H116 material available in the AUTODYN® library was used. In

the presence of the aluminium foil the impulse transferred to the structure reaches a level comparable to the other two modeled cases and experimental results.

The interaction between the incident shock wave and the test plate and the formation of the reflected wave in the central transversal section of all three tested configurations are depicted in figure 5.

The manner in which the shock wave acts on the test rig it can be observed from the data recorded with virtual transducers. The evolution of the recorded signals corresponding to the gauges position is shown in figure 6.

Also, the global assessment of rig movement indicates that the momentum is transferred to the structure in the first 0.2 ms and that after 10 ms from the initial moment the velocity induced to test rig stabilizes and fits within an evolution controlled by gravity, which means that the momentum transferred to the structure was distributed throughout the entire structure and plastic deformation of the tested plate stops.

AUTODYN® solver interface allows the extraction of relevant data on the interaction of shock wave with analyzed structures regarding the distribution of displacements, strains and stresses. The maximum equivalent plastic strain values on tested metallic plate in all three configuration after $t = 40 \text{ ms}$ is highlighted in figure 7.

Results and discussions

The first observation on the experimental results refers to the consistency of the measured data. Except the test

Fig. 4. Test stand and location of transducers for front coated polyurea

Fig. 5. Formation and blast wave propagation: a) the incident wave position at time $t=0 \text{ ms}$, b) reflected wave at plate impact at $t=0.02 \text{ ms}$, $t=0.05 \text{ ms}$ and $t=0.07 \text{ ms}$ in 3D mode

Fig. 6. The evolution of the parameters recorded by virtual sensors

Fig. 7. Iso-values of effective plastic deformation at $t = 40$ ms

with front coated plate, the transferred momentum show a good constistency even if for the coated plates it seems to be slightly higher. The exception can not be seen as an mitigation effect of the polyurea layer as the other test do

not confirm it. The probable cause of the reduced momentum for this test is the use of an already deformed and pre-cracked steel pot.

Tested configurations	Experimental test				Numerical simulation		
	Test no	Permanent deflection (transversal) (mm)	Initial Speed (m/s)	Momentum transferred (kg·m/s)	Permanent deflection (transversal) (mm)	Initial Speed (m/s)	Momentum transferred (kg·m/s)
Standard plate	1	38.2	1.712	78.886	37.43	1.736	79.7
	2	38.66	1.695	78.097			
	3	39.25	1.729	79.675			
Back coated plate	1	36.78	1.715	79.718	36.5	1.739	80.54
	2	37.43	1.732	80.515			
Front coated plate	1	37.07	1.778	82.58	36.7	1.803	81
	2	35.438	1.636	75.973			

Table 2
COMPARATIVE
ANALYSIS OF THE
MAIN RESULTS
OBTAINED

If we neglect the last test, the permanent deflection of coated plates is roughly with 4% less than the deflection of uncoated plates even if the transferred moment is slightly higher. This result is a clear effect of the polyurea layer presence. In order to assess the efficiency of the additional polyurea layer we use the theoretical curve proposed by Rotariu [18] that indicate the deflection reduction obtained for a virtual monolithic plate that keeps the mechanical properties and thickness of metallic component of metal/polyurea bilayer and the areal density of the entire structure. The permanent deflection provided by Rotariu function [18], for tested configuration, is 11.3% less than nominal one. This indicates a less efficiency for real polyurea/steel bilayer in comparison to the virtual monolithic plate.

Experimental data were also used for a thorough assesment of numerical model accuracy. The global criteria that can be expressed by numbers, the transferred momentum and the maximum permanent deflection, are compared in table 2. Regarding the shape of the plate bulge produced by the impulsive load, the graphical method is the most proper way to show the numerical model

accuracy. In figure 8 the experimental bulge profiles of the transversal section are compared to numerical results. There are no obvious differences between numerical results and experimental data.

A third category of assesment criteria are the signals aquired by sensors and gauges: accelerations and overpressures. The accelerations were time integrated in order to get the velocity. Both, experimental and numerical velocity evolution are show for a time window of 40 ms for all three tested configurations in figure 9. For first 5 ms the evolutions are quite similar for all three configurations. The discrepancy between the evolution of recorded signals, digital and experimentally, for time bigger than 5 ms can be explained due to simplified assumptions that were introduced in the numerical model. In numerical simulation, the entire structure was designed as a monolithic assembly: elements and clamping or clamping screws are neglected and the components were joined together to behave as a single body. Also, no vibration damping option was defined in numerical model.

Fig. 8. Comparison of the cross-sectional profiles for analyzed configurations

Fig. 9. Comparative analysis of velocity parameter evolution:
a) standard plate,
b) back coated plate,
c) front coated plate

Fig. 10. Comparative analysis of overpressure parameter evolution: a) standard plate, b) back coated plate, c) front coated plate

For a much shorter time window of 1.5 ms the overpressures are shown in figure 10. The evolution of these signals is presented only for the first 1.5 ms, because, after about 1.5 ms to 2 ms, the shock wave surrounds the test-bench, acting on the pressure transducer from many directions. Also, in real tests after the time $t = 1.5$ ms (the plate loading period), during the structure jump, the signal recorded by the pressure transducer is affected by the inertia of the system components. The maximum overpressure is above 200 kPa, for the bare plate and approx. 200 kPa, for coated plates.

The numerical simulations reveal the occurrence of plastic hinge on the lateral bent edges of plates near to the blast wave source where the effective plastic strain reach comparable values to those obtained in the area of the permanent maximum deflection (Fig. 7), a reason to consider the lateral bent edges as vulnerable areas of plates. The plastic hinge are not so obvious in real tests (Fig. 8), partially because the right angle with no bent radius of virtual plate edge (shell elements) is not corresponding to the real configuration where the edge is obtained through real plate bending and partially because the nodes joint option not allow a relative movement between the plate lateral sides and rigid components.

One unexpected information revealed by the simulations is related to the effective plastic strain deformation reach in the area of the permanent maximum deflection. Despite the fact that the highest permanent maximum deflection is obtained for bare plate configuration, the highest effective plastic strain deformation, around 13%, is reached for the front coated plate. This result indicates that the presence of a polyurea layer on the exposed surface it is not recommended, as long as can act as a factor that enables the steel plate failure.

The simulations also show that the considerable permanent deflections ($\cong 40$ mm deflection vs. 200 mm plate span) are obtained for effective plastic strain values relatively small (10%) for which the strength of polyurea is around 9 N/mm², corresponding to material characteristics from table 2, a considerable lower value than the specific OL50 steel yield stress.

Conclusions

Experimental studies on the behavior of shock-resistant protective materials mainly involves the generation of shock waves as a result of the detonation of explosive charges and the measurement of the effects characteristics on the structures tested according to the different experimental parameters.

The purpose of this study was to determine the ability to mitigate the effects of explosions by metal-elastomer bilayer configurations.

1/6 small-scale testing procedure based on military standard STANAG 4569 Level 3B, has showed its utility by giving useful information on the structure blast loading

process through high-speed camera and sensors data recording and post-test measurements.

For a better insight of the blast wave/structure process the numerical simulations were used. The validity of numerical models building approaches and materials models adopted was verified through a thorough comparison of real tests data with numerical results obtained by simulation (impulse transferred to the structure, plastic deformations, accelerations and overpressure).

The comparative analysis of the two sets of data reveals a satisfactory correlation between the experimental values and those determined numerically for the analyzed parameters.

Regarding bilayer configurations tested, there was not any significant improvement in the behavior of the structure as a result of its presence in any of the proposed options. In both cases the bilayered plates have shown less promising results than the monolithic steel plates of the same areal density. Moreover, numerical simulations indicate that the presence of a polymer layer on the exposed surface it is not recommended, as long as can act as an amplification factor increasing the effective plastic strain in the region where the blast wave acts.

Acknowledgements: This work is supported by the project ANTREPENORDOC, in the framework of Human Resources Development Operational Programme 2014-2020, financed from the European Social Fund under the contract number 36355/23.05.2019 HRD OP /380/6/13 -SMIS Code: 123847.

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Manuscript received: 20.06.2019