Experimental Study on Polyurea Coating Effects on Deformation of Metallic Plates Subjected to Air Blast Loads

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The paper presents an experimental study on the influence of the polyurea layer on the behaviour of metal plates loaded through air blast while the polyurea coat is placed on the loading face of the plate. To assess the influence of polyurea layer, the permanent maximal deflections of tested plates were used. A strong dependence between the effect of polyurea coating on the permanent deflection and stand-off was found. The analysis based on comparison between theoretical predictive functions and test result have shown that in almost all tested scenarios the bilayered plates results are less promising than the predicted results of monolithic steel plates of equal areal density.

Keywords: polyurea layer, blast load, plane plate, range test, overpressure

Blast-structures interaction represents a subject of great interest for the scientific community, as long as the inherent nature of explosions places such events in the category of potential dangerous situations.

The impulsive load transferred to structures is highly damaging, resulting in their catastrophic failure. A significant effort has been made in order to understand and to model the response of basic structure elements (like planar plates) for such cases. In relation with the above-mentioned issue, many papers have been published covering different topics: uniform and non-uniform loadings, scaling laws, empirical relations, analytical models, numerical simulations, failure modes, effects of explosive charges position [1-5].

Also, extensive studies were dedicated to designing improved structures, capable to sustain such loads without losing their integrity. New steel recipes, reinforcement elements, multilayer structures with metallic or polymeric foams cores, corrugated structures, composites, polymers and laminates are some of the successfully tested solutions. Usually, such experimental work is performed in lab or in test range facilities on small scale models (fasten on rigs or free) [5-10].

The wide range of mechanical properties, the adhesive characteristics and the ability to be mixed with other substances in order to obtain products with very specific functionalities in defense and security area brought the polymeric materials in the attention of researchers [11,12].

Polyurea is one of the recently developed and studied polymers with hyperelastic behavior and good mechanical properties [13,14]. The advantage of polyurea is that it can be easily applied as an additional layer on a wide range of materials: walls, floors, fabrics or metallic plates [15]. The expected benefits are related to an improved mechanical response to dynamic or impulsive loads produced by impact or explosion. The scientific literature contains a number of recent papers that analyze the performance of such multilayer structures through both practical experiments and numerical simulations [16-19].

Among the most important effects in terms of dynamic response of steel plate in the presence of polyurea layer, it can be mentioned: the initial shock alteration, the energy dissipation (based on two mechanisms: viscoelasticity and pressure and strain-induced transition from the rubbery to the glassy state), and the delay of necking onset of steel by increasing the overall tangent modulus of the plate [20-22].

One experimental study technique used in the behavior analysis of laminated plates is a modified Hopkinson bar system, which allows the application of a uniform pressure pulse (through water or polyurethane) on circular samples of multilayer material, clamped on the edges with a rigid framework [19]. One of the findings of the above-mentioned study is related to the effect of polyurea layer position on the steel plate global response: when polyurea layer is in front of the steel plate and the pressure acts directly on it, the polymer has a limited effect on the fracture resistance and on the steel plate energy absorption.

In this context, the aim of the current study is to evaluate the influence of the polyurea layer on the behavior of metal plate loaded trough air blast when the polyurea coat is placed on the loading face of the plate.

Experimental part

The experimental work was carried out in an open range testing facility. In order to generate the air blast loads, 100 grams cylindrical explosive charges (composition B) were used for each test. For the support plate, 1 mm and respectively 2 mm thickness OL EN 10130/10131 structural steel plates were used (233 N/mm^2 yield stress, 322 N/mm^2 tensile strength, 40% elongation and 7.8 g/cm^3 density). A 1.1 g/cm^3 density polyurea layer (EUROPOL®) with 4 mm and respectively 8 mm thickness was sprayed on steel plates as the coating layer.

The tested structures were provided with two rows of cylindrical holes on all the four sides. The plates were fasten by screws to a rigid rig placed on a rigid soil. The plates with polyurea layer were oriented with the coated surface facing up. The explosive charges were suspended centrally above the plates at precise stand-off. The rig was designed to block the plate movement, excepting the central section. The free moving section was a square of 200 x 200 mm. The details of test setup are indicated in figure 1.

The loading impulse variation was obtained through modification of charge stand-off. The test setup did not

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Fig. 1. Experimental setup

Fig. 2. Test configuration, overview

Fig. 3. Video capture made with camera during the test

allow a measurement of the loading impulse. In order to validate the results, a comparison of two tests with identical initial conditions (same stand-off) was performed. Thus, similar loading conditions were proved. All tests were recorded by means of pressure transducers arranged around the test location. The pressure transducers (PCB 102B06) were mounted side-on at 1 m, 2 m and 3 m distances from central axis of the test setup. The transducers were positioned at a height of 1.5 m above the ground. A test setup overview is given in figure 2. For data acquisition, a PicoScope® 6 - PC oscilloscope was used. In addition, a PHOTRON high speed camera was also used. A total of 14 tests were performed. The combinations of stand-offs and tested plates are presented in table 1.

Results and discussions

Each test was recorded using the high speed camera at 10,000 frames/second. Figure 3 presents a typical image captured by the camera. Further, all tested plates were evaluated. No sign of fracture or necking of metallic plates was observed. In just one case the polyurea layer was detached by the plate centre. All tested plates exhibited deformation with a dishing pattern in central area, right beneath the charge. Figure 4 presents the pattern deformation of plates subjected to explosions. After being removed from rig fixture, each tested plate was measured with respect to the maximum permanent deflection. The results are illustrated in table 1.

Data measured by pressure transducers were used to evaluate the loading impulse consistency. For the tests with

Fig. 4. Deformed plates pattern for test no. 11 (dorsal face)

the same stand-off, overpressure and specific impulse were compared. The specific impulse scatter was small enough to guarantee the reproducibility of loading conditions. Typical aquired pressure signal is shown in figure 5.

In order to evaluate the effect of polyurea layer, the existing tests were grouped based on two criteria:

- the same stand-off and the same steel plate thickness;
- the same steel plate/polyurea layer combination.

For both criteria, a comparison of maximum permanent deflection was performed. Normalized values of deflections are shown in figure 6 as a function of polyurea thickness. For each group of tests (grouped by first criteria) the unit value was given to the deflection of bare steel plate. As expected, the deflection reduction is higher for 8 mm polyurea layers in all cases, but the reduction is more

Table 1

TESTS CONFIGURATIONS AND RESULTS FOR 100 g EXPLOSIVE CHARGE

Test no.	Steel plate thickness [mm]	Polyurea layer [mm]	Stand-off [cm]	Permanent deflection [mm]
1	1	-	45	31.28
2	1	4	45	23.56
3	1	8	45	19.48
4	2	-	45	12.88
5	2	4	45	9.15
6	1	-	30	46.48
7	1	4	30	38.37
8	1	8	30	33.22
9	2	-	30	22.41
10	2	4	30	17.82
11	1	8	20	37.96
12	2	-	20	26.98
13	2	4	20	22.80
14	2	8	20	20.54

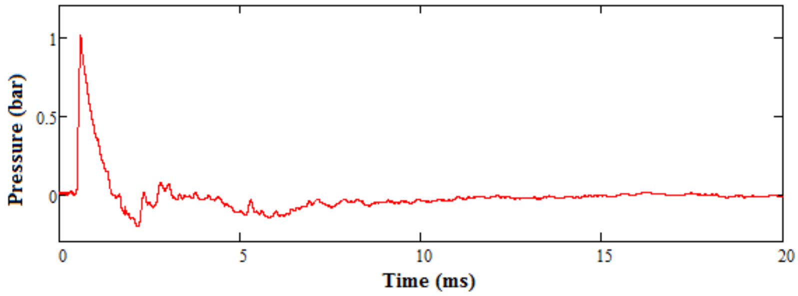

Fig. 5. Test no. 11 - Transducer no. 1

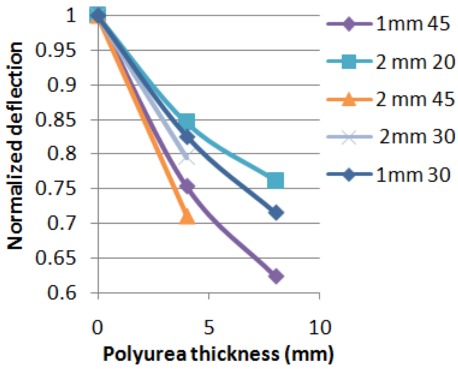

Fig. 6. Normalized deflection

abrupt for 4 mm thickness. The shapes of the curves are similar but the values of reductions differ. The dependency related to the stand-off is also emphasized.

Figure 7 shows the resulted deflections grouped by the second criteria. The similar evolutions with respect to the stand-off confirm previous observation. The gaps between the curves corresponding to the groups with 1 mm steel plate are higher than the ones which correspond to groups with 2 mm steel plate for all stand-offs. These results were expected taking into account that the structures with 1 mm steel plate are less stiff than the others. A more important observation is related to the comparison between the tests with bare 2 mm steel plate and the tests with 1 mm steel/8 mm polyurea layer. In all cases, the deflection of 2 mm steel plate is smaller. In other words, for the tested scenario, the combination of 1 mm steel and 8 mm polyurea layer is less effective than a simple 2 mm thickness steel plate, although the composite is heavier than the 2 mm plate.

Considering the above comments, a further evaluation of polyurea efficiency was necessary. A more detailed analysis has been made based on experimental findings related to the dependency between the permanent deflection of quadrangular metallic plane plates and a dimensionless damage number. In his work, Jakob [23] showed that results of a large number of tests, with uniform and non-uniform impulsive loading, admits an empirical linear relationship between relative permanent deflection of plate center and a dimensionless damage number ϕ_{q1} [23]:

$$\delta / h = 0.48\phi_{q1} + 0.277 \qquad (1)$$

where δ is the permanent elongation in plate's center, *h* is the plate's thickness, and ϕ_{q1} is given by the formula:

$$\phi_{q1} = \frac{I}{2h^2\sqrt{bl\rho\sigma_0}}\zeta_{q1}. \qquad (2)$$

The value of ϕ_{q1} is given by plate dimensions and mechanical properties through plate thickness *h*, lateral dimensions *b* and *l*, plate material density ρ and material static yield stress σ_0 and by blast loading conditions through impulse *I* and loading parameter ξ_{q1}.

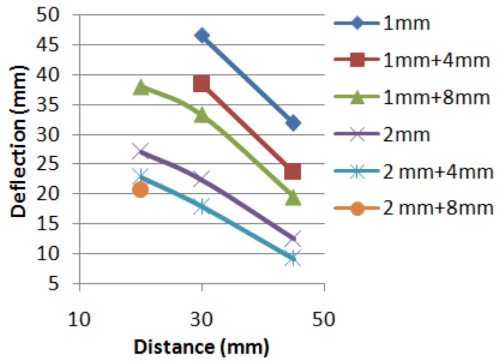

Fig. 7. Deflection values

For uniform loadings, the loading parameter takes the unit value and when the non-uniform loading conditions are meet is given by expression

$$\zeta_{q1} = 1 + \ln\left(\frac{lb}{\pi R_0^2}\right) \qquad (3)$$

where πR_2^o represents the loaded area [23].

As it was already shown, for large values of relative deformations, the 0.277 term from equation (1) becomes less than 3%, which is an acceptable error margin, and may be neglected [24]. In such cases, eq. (2) can be rewritten as

$$\delta / h = 0.48\phi_{q1} \qquad (4)$$

Eq. (4) shows that for large deflections, in similar conditions of loading, the ratio of deflections of two plane plates from the same material but of different thickness depends on thickness ratio only

$$\frac{\delta_1}{\delta_2} = \frac{h_2}{h_1} \qquad (5)$$

In the same way, if all the parameters from eq. (2) and (3) are kept unchanged except the density, the ratio of large deflections of two plane plates of different densities is given by

$$\frac{\delta_1}{\delta_2} = \sqrt{\frac{\rho_2}{\rho_1}} \qquad (6)$$

Both eq. (5) and (6) show that by adding mass, the deflection will be decreased. A similar situation is observed in figure 6. By adding polyurea on steel plate, the deflection decreased. In order to compare experimental results with theoretical curves predicted by eqs. (5) and (6) two functions were defined:

$$f_h(x) = \frac{1}{\left(1+x\frac{\rho_P}{\rho_S}\right)}; \qquad (7)$$

$$f_\rho(x) = \frac{1}{\sqrt{1+x\frac{\rho_P}{\rho_S}}}. \qquad (8)$$

Eq. (7) gives the prediction of normalized deflection of a steel plate with the same areal density like a bi-layered steel/polyurea plate of polyurea thickness/steel thickness ratio equal to *x*. Eq. (8) gives the prediction of normalized deflection of a steel plate with unchanged thickness, but the same areal density like a bi-layered steel/polyurea plate of polyurea thickness/steel thickness ratio equal to *x*. ρ_p and ρ_s represent the density of polyurea, respectively of steel. It can be see that both functions have subunitary values for positive values of *x*. When *x* tends to 0, both functions tend towards unit value.

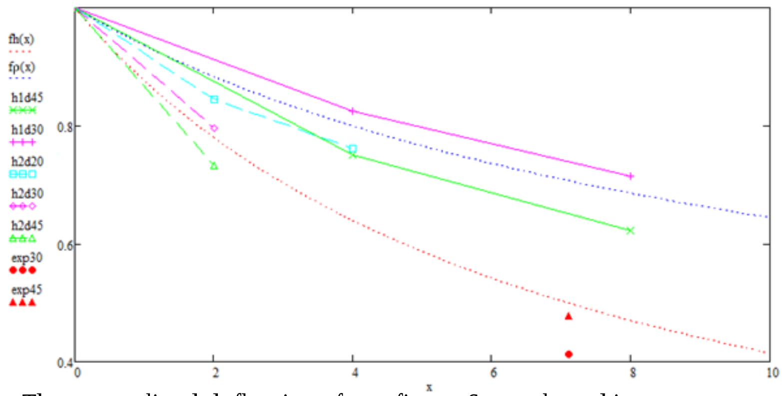

Fig. 8. $f_h(x)$ and $f_p(x)$ predicted curves compared to experimental results

The normalized deflections from figure 6 are plotted in Figure 8 as functions of polyurea thickness/steel thickness ratio and compared with curves given by eq. (7) and (8). On the same figure there are plotted two separate points that indicate the ratio between obtained deflections of 2 mm and 1 mm steel plate for 30 cm and 45 cm stand-offs. These two points are close to the $f_h(x)$ curve and confirm the eq. (5) predictions.

An immediate observation is related to the position of experimental curves in relation to eq. (7) curve. There are all above it except for the 2 mm thickness at 45 cm stand-off case. In conclusion, in terms of permanent deflection, adding polyurea layer on the loading face is less effective than a simple steel plate of equal areal density. More, the effectiveness is related to the stand-off for both 2 and 1 mm cases. At lower stand-off, it becomes less effective. In one case the effectiveness is even lower than of the curve predicted by eq. (8) (an equivalent added mass that modifies only the plate initial velocity). The relationship between effectiveness and stand-off is probably related to the applied pressure increase. This assumption is based on the observations made by Amini related to polyurea stiffness dependency on the pressure. Confined polyurea, loaded in compression, attains better impedance match with the steel plate and, consequently, the energy amount transferred to the steel plate increases [20].

The trend of effectiveness reduction does not indicate the stabilization at a given stand-off. Also, the necking phenomenon does not occur on tested metal plates, but the tests did not explore the phenomena at even shorter stand-offs as long as the tested plates at 20 cm stand-off start to show a deformed shape of fastening holes, a sign that the assumption of a blocked area surrounding of the central section is not met anymore.

It should be noted that the tests were carried out on mild steel. It is not expected that the efficiency of polyurea layers to be at the same levels on stronger metal plates as long as yielding stress is a parameter that affects the plate deflection.

Conclusions

100 g cylindrical charges of composition B were detonated at 45, 30 and 20 cm stand-off against simple mild steel plane plates of 1 and 2 mm thickness and bilayered polyurea/mild steel plates. The plates were tightly fixed on frames and presented a square area of 200 x 200 mm exposed to blast load. In bilayered configuration the polyurea layer was exposed to blast. None of the test configurations exhibited the phenomenon of steel plate necking. To assess the influence of polyurea layer, the permanent maximal deflections of tested plates were used.

The experimental findings have shown that the effect of polyurea coating on the applying pressure face is strongly dependent of the stand-off. At lower stand-off, the polyurea layer proved to be less effective.

Two equations derived from existing empirical equation that describes the relationship between relative permanent deflection of plate center and a dimensionless damage number, allowed the comparative analysis of experimental results for bilayered plates and predicted curves for simple steel plates. The shape of predicted curves is similar to the experimental curves. In almost all cases the bilayered plates have shown less promising results than the monolithic steel plates of the same areal density.

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