Resistance of GPS samples to non-contact underwater explosion

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Abstract. Test data obtained from experiments on GRP test samples in the explosion chamber of Krylov State Research Centre are given. Characteristic features of material damage accumulation and failure processes are discussed based on the experimental data. The sample material damage is assessed versus three indicative effects (criteria): binder failure, fiber rupture, through-thickness penetration (hole). Finite element modelling of the experiments is used for a more detailed analysis of stress-strain state of material samples.

Introduction

Materials of ship hull structures are subject to various kinds of loads during ship operation, including high-power dynamic loads induced by underwater explosions. In the recent years, polymer composite materials (PCM) have been increasingly used for manufacturing ship hull structures. In addition to their high strength-to-weight ratios, corrosion resistance, low heat conductivity and non-magnetic qualities these materials offer a wide choice of options to design robust structures capable to withstand both static and dynamic loads. Resistance of polymer composites to loads strongly depends on the reinforcement materials, binders, method of reinforcement, manufacturing processes, etc. PCM resistance has been widely discussed primarily in the context of quasi-static loading, while much less attention is paid to explosion-induced effects, in particular, underwater explosions (UNDEX). However, such investigations should be of interest in identification of the best PCM options for ship structures.

Various aspects of PCM responses to underwater explosions were examined in [1-12]. Analyses of PCM responses essentially rely on experimental data, and for this reason the test procedures and technologies are discussed at length in these references. In [3, 5, 6] PCM samples were loaded in a conical shock tube where micro charges were exploded to generate a plane shock wave. In [4, 8, 9] the tests were performed using a cylinder shock tube. In this case the UNDEX shock wave is generated when a heavy piston plate projected by a gas gun impacts and decelerates in water. It should be noted that in case of shock tubes the effective field of exposure to shock wave has a limited diameter of 230-250 mm, which imposes some constraints on the thickness, character of stress-strain state and types of test sample failure. The tests described in [10, 11] were conducted in an explosion chamber, test samples were mounted using special-purpose fixtures and exposed to shock waves generated by explosive charges of various masses. The tests covered in [1, 7] were performed in an open-water test range. In [1, 3-11] flat samples were tested. In [12] the results of internal explosion tests on cylinder PCM tubes are analyzed.

Along with experimental investigations, analytical methods and computer models of sample responses to UNDEX shock wave were elaborated in [2-6, 8-11], which enabled researchers, on the one hand, to verify the results of estimations and, on the other hand, to obtain additional insights from test data.
The main purposes of this study were
– to obtain test data on explosion resistance of GRP test samples exposed to a non-contact UNDEX, including evaluation of the extent and character of damage versus explosive loading parameters;
– to elaborate computer models and use computer simulation techniques for analysis of the stress-strain state of test samples as applied to given test conditions.

**Tested material and samples**
Test samples were manufactured from quadraxial glass fiber (stacking 0°/+45°/90°/-45°) and vinyl ester binder using the vacuum infusion process. Four sample batches were made and tested. Each batch contained samples of approximately uniform characteristics. Batches were different in thickness and, therefore, surface mass characteristics of samples. Characteristics of the samples are given in Table 1. The main mechanical characteristics of the composite material under study, which were obtained from static sample tests, are given in Table 2 [11].

| Table 1. Main parameters of samples |
|-------------------------------------|
| Sample batch number | Number of samples | Thickness δ, mm | Density ρ, kg/m³ | Surface mass m, kg/m² | Number of woven layers |
|----------------------|-------------------|-----------------|-----------------|----------------------|----------------------|
| 1                    | 6                 | 7.91-8.75       | 1740-1860       | 14.71-15.23          | 10                   |
| 2                    | 5                 | 7.36-7.40       | 1960-1990       | 14.49-14.69          | 10                   |
| 3                    | 5                 | 5.18-5.20       | 1970-2000       | 10.20-10.40          | 7                    |
| 4                    | 5                 | 3.66-3.75       | 1990            | 7.28-7.46            | 5                    |

| Table 2. Main mechanical characteristics of GRP |
|-----------------------------------------------|
| Characteristic | Testing direction, deg. | Symbol | Value |
|----------------|--------------------------|--------|-------|
| Modulus of elasticity, GPa | 0 | E₁ | 21.8 |
| | 45 | E₁₁₂ | 20.8 |
| | 90 | E₂ | 22.2 |
| | 0 | G₁₂ | 8.0 |
| Modulus of shear in reinforcement plane, GPa | 45 | G₁₁₁₂ | 8.9 |
| | 90 | G₂₃ | 8.4 |
| Modulus of interlaminar shear, GPa | 0 | G₁₃ | 4.2 |
| | 90 | G₂₃ | 4.5 |
| Poisson ratio | 0 | ν₁₂ | 0.29 |
| Ultimate tensile elongation, % | 0 | ε₁ | 2.6 |
| | 90 | ε₂ | 2.8 |
| | 0 | σ₁₁ | 394/371 |
| Ultimate tensile/compressive strength, MPa | 45 | σ₁₁₁₂ | 334/368 |
| | 90 | σ₂₂ | 410/357 |

The samples were circular plates of 300 to 400 mm radius. Each plate had 18 holes for bolts. Bolt setting radius was 250 mm. Samples of batches 3 and 4 were made with a circular mould-on portion in way of the bolt joints to achieve identical failure patterns for samples of different batches, i.e. to obtain damage (fiber rupture, penetration hole) in the middle of the sample and avoid any fractures at supports or near bolt joints, which are treated as accidental and largely dependent on the sample fixing arrangements. Total thickness at the mould-on portion was 14 mm.
Experimental set-up
The samples were tested in the explosion chamber of Krylov State Research Centre [10, 11]. The schematic arrangement of this facility is shown in figure 1a. The tests were performed using a so-called water-air set-up when the sample facing the explosion was backed by air-filled space. Each sample was exposed to one explosion. Every time an explosive charge was placed vis-a-vis the sample center at a fixed distance (300 mm), the charge mass Q was varied (from 8 to 90 g). The charge itself was a plastic explosive of cylinder shape with a height to diameter ratio of 1. The explosive composition was as follows: hexogen – 80 %, deterrent – 20 %. The explosive density was 1350 kg/cm, detonation velocity – 7200 m/s, TNT equivalent in terms of the specific blast energy was ~ 1. According to the relationships of [13] the shock wave acting on the test sample had the following parameters: maximum wave front pressure \( p_m = 35 \ldots 85 \text{ MPa} \), exponential decay constant \( \theta = (2.0 \ldots 3.1) \times 10^{-2} \text{ ms} \).

Figure 1b shows the test dummy assembly. The sample was fixed with 18 bolts between the matrix foundation (tubing) and clamping metal strip (ring). A rubber gasket was fitted between the clamp and the sample to seal the assembly. The effective test field diameter of the matrix-mounted sample was 400 mm. The test assembly was suspended vertically in the explosion chamber, which was filled with water so that the water surface was at least 1.0 m above the top of the assembly.

![Explosion chamber and dummy assembly](image)

**Figure 1.** Explosion chamber and dummy assembly

During the tests the strains at the back side of the sample (i.e. on the opposite side to the explosion) and blast pressure in open water were recorded. Strain gauges to record radial and circular strains were fitted at different points around the sample center over a 125 mm radius circle. The arrangement of strain gauges is shown in figure 2. Pressure readings were used to monitor the completeness of charge detonation and TNT number as well as to check that the sample strains are not affected by any wave reflections from the chamber walls.
Based on the test data, different levels of damage inflicted on samples in each test batch were correlated with the mass of explosive charges. The level of damage was assessed versus three characteristic effects (criteria): 1 – binder failure (visually identified after tests as a change in colour (bleaching) in the middle part of the sample; 2 – rupture of individual fibers; 3 – through-thickness penetration (hole). The maximum relative error in estimation of the charge mass for the damage by criteria 2 and 3 was within 15 %. In case of criterion 3 the relative error was somewhat higher, reaching 30 %, which is explained by small charge masses and test data scatter for binder failure as well as limited number of test samples.

In accordance with the above criteria three levels of explosion resistance were established for the samples. To generalize the test results obtained for the samples with different surface masses, a measure of the explosion effect was introduced: relative charge mass $\beta = \frac{m_{ex}}{m}$, where $m_{ex}$ is the mass of charge per unit of the sample’s test area, kg/m$^2$; $m$ – surface mass of the sample, kg/m$^2$.

Thus, the relative charge mass triggering one or another kind of failure is taken as a measure of specific explosion resistance of the samples.

**Discussion of test results**

Figure 3 shows photos of typical failure patterns of samples, and Table 3 contains the relative masses of charges characterizing different explosion resistance levels of samples.

**Figure 2.** Arrangement of the strain gauges on the sample

![Figure 2](image_url)

**Figure 3.** Typical damage patterns of samples

- **a)** Binder failure, back side
  
  $(Q = 8 \text{ g}, \beta = 0.44\%, \delta = 7.32 \text{ mm}, m = 14.49 \text{ kg/m}^2)$

- **b)** Fiber rupture in three layers, back side
  
  $(Q = 70 \text{ g}, \beta = 3.83\%, \delta = 7.40 \text{ mm}, m = 14.50 \text{ kg/m}^2)$

- **c)** Hole, front side
  
  $(Q = 55 \text{ g}, \beta = 4.20\%, \delta = 5.20 \text{ mm}, m = 10.40 \text{ kg/m}^2)$
As the explosion power (charge mass) is progressively increased it is seen that binders of test samples start to fail, first in the center and in the supported portion of a sample, then this damage spreads over the entire test area of the sample (figure 3a). It follows by rupture of individual glass fibers in the middle part, starting from the back layer. At this stage the fiber rupture is mostly chaotic (figure 3b). Finally a through-thickness penetration hole is formed by two main intersecting fractures propagating at about $\pm 45^\circ$ to the reinforcement fiber material (figure 3c). The through-thickness penetration failure refers to approximately the same specific explosion resistance across all test batches of samples with a difference of less than 15%, which practically falls within the test data error. It should be noted that samples of less thickness demonstrate a somewhat higher explosion resistance in terms of this criterion, apparently because of lower bending strains. However this difference is small, e.g., if the sample thickness is doubled, $\beta_2$ changes only within 20%.

The energy absorption capacity of samples before initiation of fiber ruptures is mainly governed by the binder failure. Thus, after initiation of binder failure the relative charge mass has to increase more than 5 times to cause a through-thickness penetration, while after initiation of fiber rupture only a 10 to 40% increase is sufficient to initiate this type of failure. Two comparative tests with batch 2 samples were performed to confirm the effect of binder failure on the energy absorption capacity of samples. In one case the sample was first subjected to a 8 g charge explosion ($\beta=0.44\%$). Here, the binder failure occurred (from the back side throughout practically the entire test area, from the face side in the area of the support contour) but no fiber ruptures were observed. Then the same test sample was subjected to a 70 g charge explosion ($\beta=3.83\%$), which resulted in the hole. In the second case, the similar sample was subject to a single explosion of a 70 g charge ($\beta=3.83\%$). Here, the explosion produced no hole, resulting only in fiber ruptures from the back side at the center of the sample. Thus, preliminary shock effect on the sample (causing a binder failure), has drastically reduced its explosion resistance in terms of the 2-nd and the 3-rd criteria.

Figure 4 presents characteristic time histories of strains for samples from different test batches under different exposure levels $\beta$: 0.44% (Q=8 g, $\delta=7.32$ mm); 1.04% (Q=20 g, $\delta=8.75$ mm); 1.64% (Q=15 g, $\delta=3.66$ mm); 3.27% (Q=60 g, $\delta=7.36$ mm). For each test ($\beta$ value) the figure gives readings of 2-3 strain gauges installed at different points over a circle of $r=125$ mm (see figure 2).

Regarding the strain measurements the following should be noted. For the explosion power range under consideration it is seen that in spite of damage accumulation (failure of binder, fiber ruptures), in general, the test samples do not practically show residual strains at the measurement points or residual deflections, which makes it possible to further model GRP as a linear elastic. The transitory process of sample straining lasts 2-4 ms. This duration depends on both frequency parameters of the samples and the explosion loading level. The time of transitory process decreases as frequency and explosion loading level grows. The latter circumstance is related to the increasing effect of chain radial strains. The maximum radial strains at the measurement points are $\sim$2-2.5 times higher than the circumferential ones. At the explosion loading level initiating the fiber rupture in GRP samples ($\beta=3.27\%$), the maximum radial strains reach 2.8%. At the center of the sample, where the strains are the greatest, this value is even higher and exceeds the limit relative elongation of the material under consideration (2.6-2.8%, see Table 2). The strain measurement data was used to validate the computer-based analytical models.
Figure 4. Strain versus time at different explosive loading levels $\beta$

Figure 5 shows a typical time history of pressure in the explosion chamber during the tests. Analysis of the pressure records showed that parameters of dynamic sample loading were not affected by any wave reflections from the test chamber walls. The experimental pressure curve was compared versus the calculated parameters of a TNT explosion in the infinite fluid. The calculation was performed using the empirical relationships from [13, 14]:

$$p(t) = \begin{cases} p_m & \text{for } t \leq \theta \\ 0.368 \frac{Q}{t/\theta} & \text{for } t > \theta \end{cases}$$

where $p_m = 52.4 \left(\frac{3\sqrt{Q}}{r}\right)^{1.13}$, MPa, $\theta = \frac{m}{c_0} \sqrt{\frac{r}{\eta_0}} - 0.9$, s, $\eta_0 = 0.053 \frac{3\sqrt{Q}}{Q}$, m, $c_0 = 1500$ m/s – velocity of sound in water, $r$ – distance from explosion center to measurement point, m.

Figure 5. Experimental and analytical pressure of explosion: 1 – shockwave front, 2 – wave reflected from the sample, 3 – wave reflected from the chamber walls

The comparison of the test results with the analytical data shows that the charge detonation during the experiments was complete, and the explosion parameters were in a good correlation with the
empirical relations for TNT charges, which enabled us to assume Jones-Wilkins-Lee (JWL) equation with empirical TNT parameters for the test explosive charges in our computer-based simulation of the experiment [15].

**Computer simulation of the experiment**

The purpose of the computer-based simulation was to develop analytical FEM-based models for adequate prediction of strain behavior for composite materials exposed to UNDEX, as well as to apply these models for a more detailed stress-strain analysis of the samples during the tests. The necessity to apply computer-based models in stress analysis is required, among other reasons, due to limited availability of experimental sample strain data: in particular, when the explosion occurs near the sample, strains are practically impossible to record on the front side of the sample, and even on its back side (at the center of the sample).

Computer simulations of UNDEX and its effects on obstacles have been discussed in sufficient detail in many papers. Specifically, various aspects of computer simulations using commercial and in-house software were considered in [16-25], etc.

The processes invoked by a proximity non-contact UNDEX are quite complicated, so in this paper the test conditions were simulated using two FEM-based programs: LS-DYNA and AUTODYN. The formulation of the problem was three-dimensional in both cases. Since the samples were symmetric, only a quarter of the test area was simulated: a segment of fluid (water) with radius of 660-900 mm and height of 810-1050 mm with the cut-out in the upper part running along the contour, its size being equal to overall dimensions of the tubing (see figure 6). The sample was put inside the cut-out, and above the sample, there was air-filled space corresponding to the free volume in the tubing behind the sample. The design diameter of the sample was assumed as equal to the bolt joint diameter, i.e. 500 mm.

![Figure 6. Computational domain in the test simulation](image)

Simulation in both LS-DYNA and AUTODYN was performed with the same boundary conditions and the same types of finite elements. The boundary condition of zero normal velocity was specified for the air-filled space, the contour simulating the tubing was assumed to have solid and zero-normal-velocity boundary conditions, the water space was assumed to have the free-stream boundary. The boundary condition for the sample was specified as “no displacements normal to the sample plane throughout the 50 mm wide ring”, which ensured the same test area of the sample as in the actual tests. All the objects – sample, water, air, charge – were simulated by means of SOLID-type finite elements, the Euler mesh was used for water, air and charge, and Lagrange mesh – for the sample.

Mesh parameters (size, aspect ratio, density) were selected so as to have little effect upon the calculation results. In particular, characteristic size of the Euler mesh for water and air near the sample was ~4-5 mm, the size of the Lagrange mesh in the plane of the sample was 3.4 mm, the characteristic number of elements through the thickness of the sample was 6.
Equation of condition for the water was polynomial:

\[ p = A_1 \mu + A_2 \mu^2 + A_3 \mu^3 + (B_0 + B_1 \mu) \rho_0 e \]  
\[ p = T_1 \mu + T_2 \mu^2 + B_0 \rho_0 e \]

where \( \mu = \rho_1/\rho_0 - 1 \), \( \rho_1=1000 \, \text{kg/m}^3 \) – current and initial densities, respectively, \( A_1, A_2, A_3, B_0, B_1, T_1, T_2 \) – empirical constants, \( e \) – internal energy per unit mass. The following constant values were assumed: \( A_1=2.2 \, \text{MPa} \), \( A_2=9.54 \, \text{MPa} \), \( A_3=14.57 \, \text{MPa} \), \( B_0=B_1=0.28 \), \( T_1=A_1 \), \( T_2=0 \). The initial internal energy with reference to the atmospheric pressure of 101.3 kPa was assumed as \( e_0=361.8 \, \text{J/kg} \). It was assumed that the pressure in fluid cannot be negative. This assumption is the simplest way to consider cavitation phenomena in fluids due to explosion processes.

Air was modelled by the equation of ideal gas state \( p=(\gamma-1)\rho e \), where the adiabatic exponent is \( \gamma=1.4 \). It was assumed that \( \rho_0=1.225 \, \text{kg/m}^3 \).

The explosion products were simulated using JWL equation

\[ p = A \left( 1 - \frac{\eta \omega}{R_1} \right) e^{\frac{-R_1}{\eta}} + B \left( 1 - \frac{\eta \omega}{R_2} \right) e^{\frac{-R_2}{\eta}} + \omega \rho e, \]

where \( \eta = \rho_1/\rho_0 \), \( \rho_1=1630 \, \text{kg/m}^3 \), \( A \), \( B \), \( R_1 \), \( R_2 \), \( \omega \) – empirical factors. Empirical factors and Chapman-Jouguet parameters for TNT were assumed as [15]: \( A=371.2 \, \text{GPA} \), \( B=3.231 \, \text{GPA} \), \( R_1=4.15 \), \( R_2=0.95 \), \( \omega=0.3 \), \( \rho_{\text{CJ}}=21.0 \, \text{GPA} \), \( D_{\text{CJ}}=6930 \, \text{m/s} \) – detonation velocity, \( \bar{c}_0=7000 \, \text{MJ/m}^3 \) – initial internal energy per unit volume (\( e_0 = \bar{e}_0/\rho_0 = 4.29 \, \text{MJ/kg} \)).

The underwater explosion effect upon the sample was simulated in two stages. The first stage was the investigation of an explosion in the free infinite fluid in uni-dimensional (AUTODYN) or two-dimensional (LS-DYNA) formulation. In this formulation, the calculation was performed up to the moment corresponding to the shock wave approach to the sample. Then, this solution was exported into a 3D model including the sample, and the second stage of calculation followed.

GRP was treated as a quasi-isotropic material with linear elastic properties. For valid comparison with the test results the sample characteristics (thickness, density, modulus of elasticity, etc.) were assumed to be the same as in the test under consideration.

Computer models were validated using the strain time histories recorded during 9 tests on batches 1 to 4. The mass of charge in the experiments was \( Q = 8, 10, 15, 45 \) and 60 g. Figure 7 compares analytical and experimental time histories of radial and circumferential strains for a sample of batch 1 (\( \delta=8.75 \, \text{mm} \)) at explosion of charge \( Q=10 \, \text{g} \).

![Radial and Circumferential Strains](image)

**Figure 7.** Calculation vs experiment: \( Q=10 \, \text{g}, \delta=8.75 \, \text{mm} \)

a) radial strains (RC=0.14 – for LS-DYNA; RC=0.18 – for AUTODYN)  
b) circumferential strains (RC=0.10 – for LS-DYNA; RC=0.22 – for AUTODYN)
Quantitative assessment of the convergence between the calculation results with the test data was performed as per the approach suggested and justified in [26]. As per this approach, integrated coefficient of convergence between two unsteady processes (e.g. experimental and analytical) is determined as follows:

$$RC = \sqrt{\frac{\pi}{4} \left( RM^2 + RP^2 \right)},$$

where $RM = \text{sign}(m) \frac{1}{g(1+|m|)}$ and $RP = \frac{\cos^{-1}(p)}{\pi}$ – divergence by amplitude and by phase, respectively, $m = \frac{A-B}{\sqrt{AB}}, \quad p = \frac{C}{\sqrt{AB}}, \quad A = \sum_i f_1(i)^2, \quad B = \sum_i f_2(i)^2, \quad C = \sum_i f_1(i) f_2(i)$, $f_1(i)$ and $f_2(i)$ – amplitudes of the experimental and simulated process, respectively, as determined for the same time instant $i$. Ref. [27] suggests the following gradation for the integrated $RC$ coefficient: if $RC \leq 0.15$, the convergence is deemed excellent, if $0.15 < RC \leq 0.28$, the convergence is deemed acceptable, and if $RC > 0.28$, the convergence is deemed poor.

Figure 8 gives calculated $RC$ coefficient for radial and circumferential strains in 9 experiments with GRP (triangles and circles denote the calculation results as per LS-DYNA and AUTODYN respectively) [11]. As it is seen from this figure as well as from figure 7 calculation results have rather a good correlation with the experiment. Only in 4 cases for LS-DYNA and in 2 cases for AUTODYN the coefficient was $RC > 0.28$. Some deviation between the calculation and the experiment, as well as between the calculations in LS-DYNA and in AUTODYN can be due to different accuracy in evaluation of explosion parameters at the initial stage between LS-DYNA and AUTODYN, errors in modelling boundary conditions for samples, evaluation of actual sample thickness, discrepancy in coordinates of strain and locations of strain gauges.

$$a) \text{ radial strains} \quad b) \text{ circumferential strains}$$

**Figure 8.** Integrated coefficient of convergence between calculations and experiment

The developed computer models were used for more accurate stress analysis of the samples during the tests. Figures 9 and 10 illustrate estimates of sample deflection behavior in the process of deformation. Three phases of the process can be identified. First (at the initial instant at $t=0.1$ ms, see figure 10b) the sample is mainly deformed around supports by bending and shear. The middle part is practically intact and moves as a solid body. In the second phase, deformation waves (shear, bending and tension) propagating from the supported contour reach the central part of test sample. In this case the sample assumes a sine-like shape along its radius (figure 10). Further, in Phase 3, the sample continues to deform mainly retaining the same shape of deflection. The local peaks of deflections in the center of test sample (figure 9) are caused by appearance and disappearance of cavitation areas on the sample. The above phases of deformation process are characteristic for the conditions when the sample surface is subjected to a distributed dynamic load of shock wave type [28].
Figure 9. Deflection of sample center in function of time, $\delta = 8.75$ mm

Figure 10. Shape of sample deflection (along radius) at different instants in time, $\delta = 8.75$ mm

An important consideration in the limit state estimations is the level of sample strain. The chain and bending strains (figure 11), as well as strain intensities (figure 12) in the sample center and at the support were considered. The analysis of calculation results shows that even the samples of relatively large thickness (batch 1, $\delta = 7.91-8.75$ mm) feature a high level of chain strains. The maximum value of chain strains is practically equal to bending strains, and is approximately 2% at 60 g charge explosion (tentatively initiating rupture of individual fibers). In this case the sample deflection is about 50 mm. Bending strains are prevalent in the supported area, exceeding 5 to 7 times the level of chain strains. The maximum level of total radial (bending + chain) strain at the support is about 1.5 times higher than at the sample center.

In accordance with the test data, samples are first damaged in the center (rupture of fibers) in spite of higher radial strains at the support. However, if we compare the strain levels by von Mises criterion these strains are approximately 1.5-2 times higher at the center as compared to the support. At the initiation of fiber rupture von Mises yield reach 5% in the center of samples, which is twice the ultimate relative elongation of static samples. It can be assumed that the von Mises yield stress can be used to evaluate the explosion resistance (based on fiber rupture criterion) for the polymer composites manufactured by vacuum infusion process and featuring quasi-isotropic properties provided by their reinforcement structure.
Figure 11. Chain and bending strains: calculation results, $\delta=8.75$ mm

Figure 12. von Mises yield strains: calculation results, $\delta = 8.75$ mm
Conclusion
The paper presents the results of experimental and computational studies conducted to investigate underwater explosion resistance of GRP samples made of quadraxial glass fiber and vinyl ester binder. The samples were tested in the explosion test chamber of Krylov State Research Centre. The sample material damage was assessed versus three indicative effects (criteria): binder failure, fiber rupture, through-thickness penetration (hole). The relative explosive charge mass (charge mass per unit effective area of sample related to sample surface mass) is taken as a measure of explosion effects causing a certain type of material damage. It is confirmed experimentally that the specific explosion resistance of the test samples up to through-thickness penetration is largely defined by the energy level initiating the fiber rupture process. Computer simulation models were developed and validated to enable more detail analysis of stress-strain states of tested samples. In particular, the computer simulations indicate that the von Mises yield criterion can be used to assess the explosion resistance (initiation of fiber rupture) for samples under study. It should be noted that von Mises strain exceeds approximately two times the ultimate relative elongation of static samples.

The above-presented experiment in modelling UNDEX effects should be useful for the analysis of stress-strain states and failure processes of samples and structures made of various GRP materials.

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