IMPACT DAMAGES AND HEALING OF GFRP SANDWICH SKIN

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Abstract

Experimental studies of ballistic impact with different velocities were done for GFRP plates (plain glass fabric with epoxy matrix) as sandwich panel skin. For this purpose there was designed and made the table-top stand for accelerating steel ball with a diameter of 8 mm up to 600 meters per second by using of energy of standard dowel hammering cartridge. There were observed crosscutting damage (high velocity impact) and the delamination (low velocity impact) with minimal damage of outer layer fibers. For healing of delamination, we offered the use of ultrasound excitation for sucking of liquid matrix drop into small hole drilled in delamination zone. Strength restoration for CAI test is 80-90%. There was also developed the numerical 3D model of GFRP to calculate ballistic curve with getting V_{50} as ballistic limit. This model consists of SHELL elements for curved glass threads and SOLID elements for matrix.

Introduction

Issues related with the account of various damages during exploitation of composite structures are highly relevant as well as the development of methods to healing them.

In most of the studies described [2-13], there were covered various aspects of the loading of composite structures (panels), and aspects of damage modeling. Davies and Zhang [14], and also Schoeppner and Abrate [15] had conducted instrumented tests to show influence of various parameters including panel thickness. The authors focused on the concept of the maximum critical force as a reason of defects. The tests had conducted using a drop tower.

Nowadays, structural approach is based on modeling each fiber by SHELL or SOLID finite elements for predicting the impact strength of several layers of composite material [16]. Simulation of threads individually enables to contact with neighboring threads and indenter. It allows to simulate the motion, deformation and failure of each thread [17].

SHELL for individual threads were using in many studies. Elliptical cross-section of thread was modeled by several adjacent shell elements with different thicknesses [18]. However, in the formulation of such models it is complicated to manage contact conditions between treads, cause shell elements with different thicknesses have a gap in the corresponding boundary conditions.

The threads in the fabric can also be divided by solid finite elements [19]. However, such models have larger dimension.

There are studies where the region near the contact of the indenter with multilayer plate is modeled in details, and the outer zone is replaced with solid anisotropic media with larger size finite elements [20, 21]. This approach helps to save processing resources, gives the opportunity to calculate the deformation of large plates with several layers, but the results cannot be trusted because miss the opportunity to slip the fiber. As the studies of E. Kharchenko [22], it takes up to 50% of the energy of the indenter to pull fibers out of fabric.

Significant difference between high and low-velocity impact explains by Jackson and Poe [23]. They define the differences between quasi-static load impact with a large-mass and low-mass dynamic loading. In particular, the dynamic loading of the small mass occurs at a sufficiently high speed, then it is necessary to consider wave effects, and the boundary conditions have little effect. When loading occurs with large massive strikers speed of impacts is much smaller and loading, as was shown by the authors, remind quasi-static indentation. Thus, the result mainly depends on the boundary conditions.

Currently, there are no such models, which can be applied simultaneously to describe the high-velocity (HVI), and a low-velocity impact (LVI). Scientists are mainly engaged in the development of models which describe breakdown the sample [9, 14] or simulate quasistatic processes under low speed impact. In this case, when the damage is border character (breakdown or no breakdown), and speed of the impactors is close to the ballistic limit these models are ineffective. The observed destruction mechanisms in real materials such models take into account bad.

To better describe the model structures and set the properties you can use Composite Pre/Post, PAM-FORM, in which you can create composite structures, given the different stacking layers for analysis of dynamic loading. These packages have the ability to set the anisotropic properties of materials and offer a wide selection of current criteria for evaluating destruction. However, to construct models in such packages must specify a large number of parameters that is a disadvantage due to lack of methods for determining these parameters.

1. Investigation of damage mechanisms of GFRP on impact

The GFRP plates were fired at the stand [24] (Figure 1), to study damages at the ballistic loading. In our stand, we used powder energy of standard dowel hammering cartridges (series D and K). The energy of these cartridges varies from 300 to 1000 Joule, which is enough to accelerate of spherical steel impactors with a diameter of 8 mm (weight 2.2 g) until speed of 700 m/s.

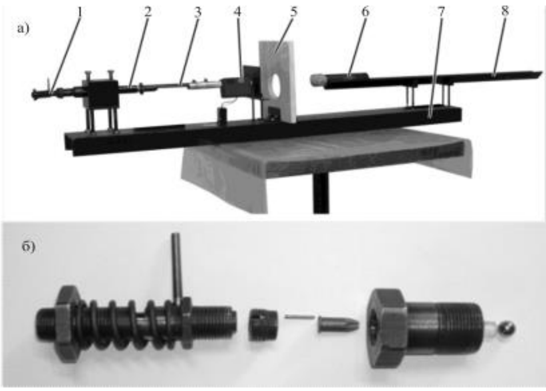


Figure 1. Table fire stand (protective cover removed): a) - 1 – trigger, 2 - barrel, 3 - vent tube, 4 - chronograph, 5 – target place, 6 - friction trap, 7 - base; 8 – trap rail, b) the bolt and breech with the projectile.

Experiments were provided with different initial velocity of a spherical impactor. Velocity was varied in the range from 250 to 600 m / s. HVI (or ballistic) creates damages which are typical things in the battle practice. The hole-like damages formed after bullet impacts are included in the calculation schemes (main safety factor ~2). BVI (barely visible impact) is very valuable to weight reduction (additional safety factor) and was investigated in this work. For FRPs we see an intense delamination and fiber failure. Types of damage are shown on Figure 2.

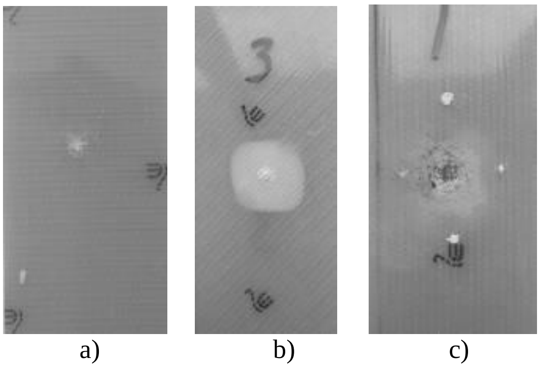


Figure 2. Types of damage of composite: a) BVI ; b) intermediate; c) HVI.

Figure 6 shows the ballistic curve of samples made of GFRP material trade mark 'STEF' by steel spherical impactor with a diameter of 8 mm, obtained at this stand [24].

2. Dynamic tests to determine the tensile strength

Dynamic tests on a vertical drop tower Instron CEAST 9350 were conducted to obtain the dependence of the tensile strength from the strain rate (Figure 3) and were compared with experiments at static tension obtained on the universal testing machine Instron 5882.

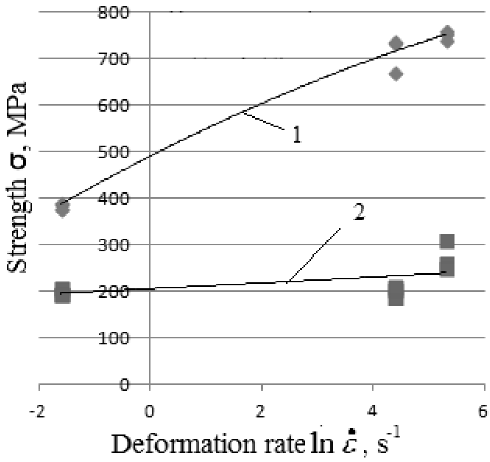


Figure 3. Dependence of tensile strength on the strain rate: 1 - for the samples at an angle of 0 degrees, 2 - sample 45 degrees.

As you can see on the graph, the strain rate exerts a substantial influence on the strength properties of the composite. Strength growth under dynamic stretching along fibers shows the increasing of the fibers strength. During tests of samples cut at 45 degrees, the strength of the composite increases due to the increasing of shear strength of the polymer.

3. Numerical modeling

In this paper, we offered an intermediate model of GFRP STEF, which takes into account the curvature of fibers and the existence of two different components. The fibers were presented in the form SHELL-elements, and the matrix- in the form of Solid- elements (Figure 4). This representation allows to simulate the composite delamination and fracture.

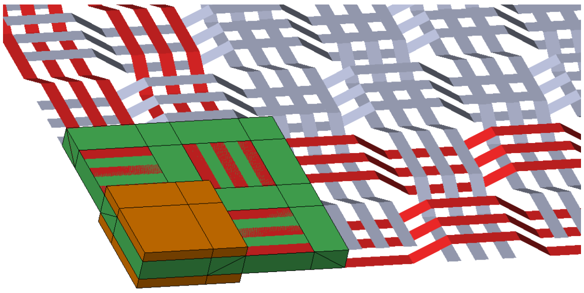


Figure 4. Model in Solid Works.

3.1 Set the properties of the model

When a numerical model was creating, elliptical cross-sectional shape of fiber was replaced by a rectangle one with the dimensions of the fibers as shown on Figure 5. Corrugated fiber axis was replaced by a piece-wise line with straight horizontal and sloped sections.

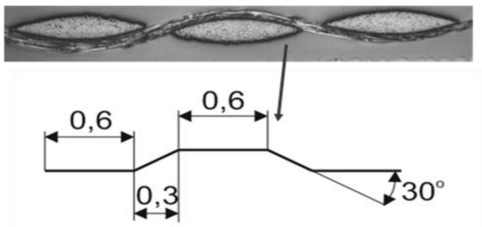


Figure 5. The fiber scheme (mm).

Calculations were carried out with ANSYS LS-DYNA software package. In our model, the fracture criterion is the excess of first principal stress σ_{max} specified the limit value σ_b (composite materials is almost perfectly elastic and brittle). Value σ_b were assigned on the results of dynamic tests and were equal to the fiber 8 GPa and to the resin 120 MPa.

3.2 Results of simulation

Ballistic curve was obtained by results of calculations and were compared with the experimental data. As it can be seen from the graph (Figure 6), the calculated ballistic curve has the good agreement with experiment.

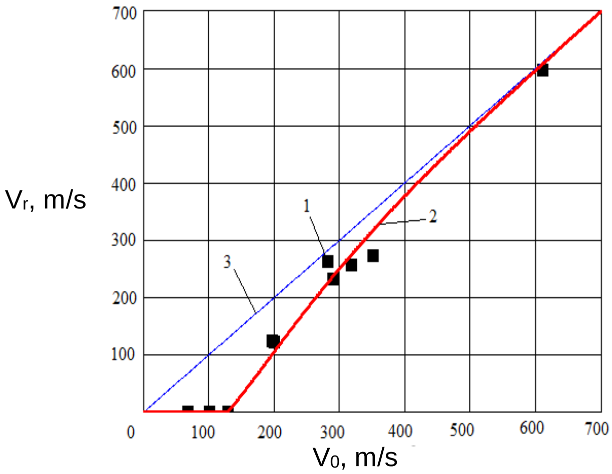
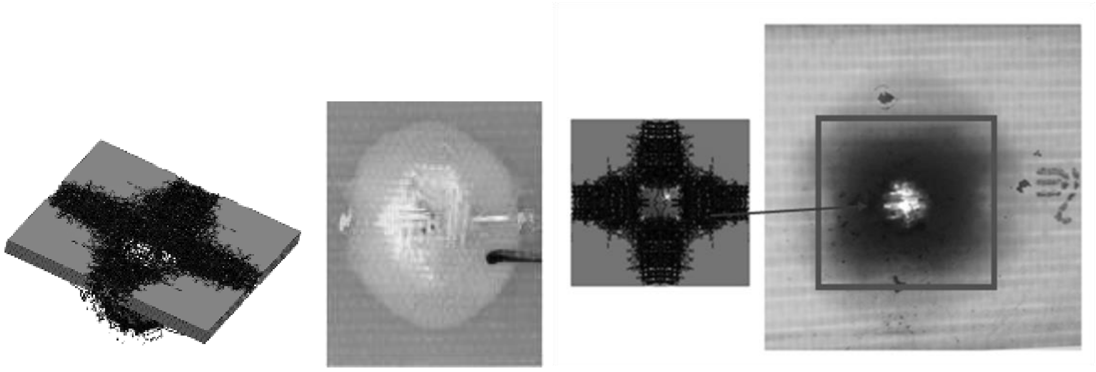


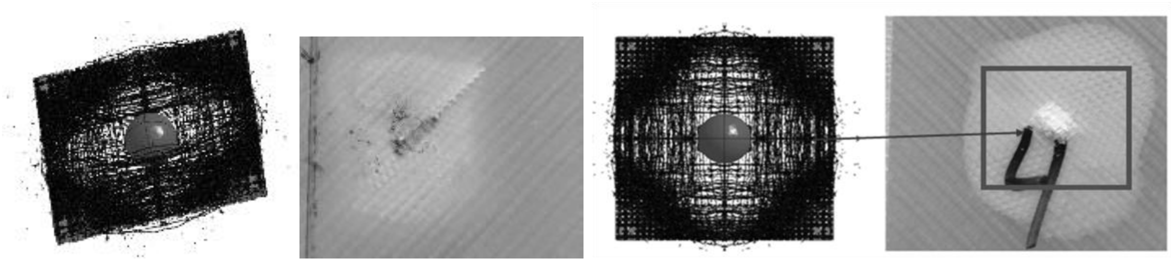
Figure 6. Comparison of ballistic data: 1 - experiment; 2 - calculated curve; 3 - absence of the target.

Various fracture mechanisms at different impact velocities were obtained by simulation. Comparison of calculated and experimental pattern of damage of the plate shown in figures 7 and 8.



a) b) c) d)

Figure 7. Comparison of pictures for a speed of 350 m/s: calculation: a) and c); experiment: b) back reflective d) translucent.



a) b) c) d)

Figure 8. Comparison of pictures for a speed of 100 m/s: calculation: a) and c); experiment: b) face reflective, d) back reflective.

4. GFRP healing after a low-velocity impact

It is difficult to estimate a zone of internal delamination for layered fibreglasses with opaque structure and at small damage. Therefore, an experimental study of such damages (only internal delamination) was investigated using infrared camera TESTO 875.

Heating of the sample occurred 1 kW photo lamp during 10 seconds at a distance of 0.2 meters.

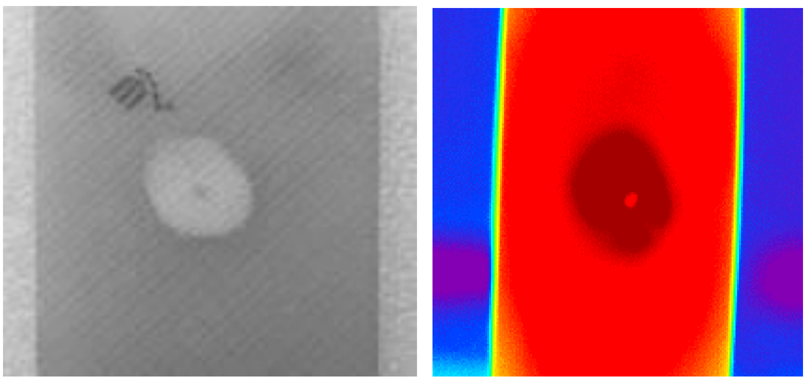


Figure 9. Investigation of visible damages (left) and internal ones (right) by IR camera.

The hot zone on the screen (Figure 9) shows the area of delamination of the sample.

Variants of healing composite materials have been discussed in several papers [26, 27]. In this paper, we proposed a new method of healing BVI of GFRP. The method is based on the use of ultrasonic device. The damage must be only a delamination without failure the fibers. This is due to the fact, that healing occurs by means of filling the gaps between the layers by epoxy resin. The epoxy resin will bond layers together and provide undamaged condition. For better penetration of resin and spreading it into gaps, we used the ultrasonic laboratory exciter (Figure 10) with power of 0.2 kW and 18 kHz oscillation frequency.

Figure 10. Ultrasonic exciter.

In operation, the exciter heats the resin, increases its fluidity, thereby improving the impregnation of resin into the zone of the delamination by the action of surface wetting. For better penetration of resin, we propose drill out the several small holes with a diameter of about 0.3-0.5 mm. It is known that small holes do not reduce the strength, that is not cause considerable additional damage, but help to better impregnate sample by epoxy resin. Studies have shown is necessary to drill holes at the edges of the delamination zone because directly under the impact point delamination is not observed (Figure 11).

Figure 11. Transversal section of impact area. Delaminating cracks highlighted by black ink.

As a result, after the healing, GFRP strength increased to 80-90% of pristine. Figure 12 shows a sample before and after healing.

Figure 12. Sample before (left) and after healing (right). Small holes are visible.

Conclusion

1. There were provided ballistic tests for study deformation and failure of composite material STEF (GFRP) at high- and low-velocity impacts. The ballistic limit is 140 m/s.
2. The mechanical characteristics of STEF at a dynamic with loading speed of 2 and 5 m/s were studied. Increasing of the tensile strength along warp and weft fibers was approximately 70-80% above the static experiment; for shear test increasing was about 50%. This fact proves that the strain rate influences on the strength of GFRP.
3. There was proposed a new method of healing delamination of GFRP plates. The method is based on the use of ultrasonic exciter's help for resin transport into cracks. As a result, post healing GFRP strength is about increased to 80-90% of pristine.
4. There was offered the simple variant of microstructure modeling, which showed the possibility of calculating the impact resistance of GFRP plate at low and high velocities.

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