Properties and destruction of anisotropic composite materials under static deformation and impact loading conditions

N V Korneeva¹, V V Kudinov², I K Krylov², and V I Mamonov²

¹Laboratory of Fiber Reinforced Plastic, Semenov Institute of Chemical Physics of the Russian Academy of Sciences (IChPh RAS), 4 Kosygin St., Moscow 119991 Russia
²Baikov Institute of Metallurgy and Materials Science of the Russian Academy of Sciences (IMET RAS), 49 Leninsky prospect, Moscow 119334 Russia

E-mail: natakorneeva@mail.ru; kudinov@imet.ac.ru; igorgra04@gmail.com; voletic@mail.ru

Abstract. A new approach toward understanding failure mechanisms of anisotropic fiber-reinforced composite materials due to low velocity impact is discussed. The dependence of failure mechanisms and mechanical properties of such composites on loading velocity are examined by Impact Break method. It has been shown experimentally that especially large change in the CM properties occurs in the transition from static to impact loading conditions. CM destruction was observed at the first moment of a shock load application. The relaxation of the stresses in CM and the energy dissipation from breaking fibers are limited the short duration of impact value equal to 1-2 ms. Failure mechanism is based on the fibers stretching and stress-wave propagation through the CM under impact. The processes of multi-breaking and crushing of the filaments are imposed on the process of multi-stage stretching deformation. It led to decrease CM properties as compared with that under static. In a static situation, the deformation of CM is mostly stretching deformation. It gradually grows as the load increases. It has been found out that specific absorbed-in-fracture energy of CFRP and OFRP under impact loading conditions is significantly reduced by factors of 3.7 and 3.2, respectively, as compared with that under static ones. As a result, the choice of CM to create structures based only on the static properties of the material does not guarantee the impact resistance of structures upon low-velocity impact.

1. Introduction

The velocity of loading strongly affects the mechanical properties of anisotropic fiber-reinforced composite materials (CM). Especially large change in the CM properties occurs in the transition from static to dynamic loading conditions. Now the importance of materials anisotropy is recognised and failure theories suggested by Puck (1965) and Tsai (1984) are well known. However, the heterogeneous character of anisotropic CM is often neglected [1-3].

It is well known, that ASTM D256 standard for Izod impact testing is applied for loading plastics. The data provided tests for isotropic materials, may not be suitable for reinforced composites due to the material anisotropy [3,4].

Fiber-reinforced plastic (FRP) may consist of various components with a large difference in chemical nature. Unlike isotropic materials, such composites have complicated failure mechanisms.
The failure modes are fiber breakage, matrix cracking, fiber/matrix interface debonding and delamination.

The fibrous composites are strongly anisotropic materials. CM strength and stiffness are provided by the reinforcing fibers or fabrics and the integrity and environmental resistance of the CM are contributed by the matrix. The matrix transfers the load on the reinforcing fibers, redistributes the stresses between them and consolidates the monolithic material. The time of these processes is drastically reduced to 1-2 ms under impact. This limits the stress relaxation and energy dissipation at break of the fibers. That is why impact is an unsafe load type because it is catastrophic quickly reduced the high performance characteristics of CM.

Impact Break (IB) method for investigation of the properties of anisotropic fiber-reinforced composites by means of shock tests of special CM sample with the help of pendulum impact testing machine was developed [4-7]. The IB method is the most perspective for determination of the CM properties such as the longitudinal and relative deformation, specific absorbed-in-fracture energy, ultimate tensile strength, shear strength of the fiber to the matrix upon impact. The IB method allows one to predict of CM properties under impact loading conditions and their use in structures [5-9].

The purpose of the research was to study the failure mechanisms and mechanical properties of anisotropic fiber-reinforced composite materials under static and dynamic loading conditions by the IB test.

2. Experiment

Impact tests were carried out by IB method with the help of transversal impact on the impact pendulum-type testing machine Roell Amsler RKP-450 with computer-controlled and continuous recording of dynamic curve load - deformation, in this case load - flexure (bending). The impact velocity was 5.25 m/s. The shape of impactor head was with radius \( R = 3 \) mm.

Static tests were performed on an Instron 3382 universal testing machine at a cross-head speed of 5 mm/min \( (8.5 \times 10^{-5} \) m/s) by using a tensile test. The results obtained under impact are compared with that under static loading conditions.

The failure mechanisms and mechanical properties of CM upon impact may be studied using an IB-sample. It can be defined as a single bundle of filaments micro-composite, subjected to impact [7]. Reinforcing continuous multifilament fiber (a single bundle of filaments) is located unidirectional in the single-layer and impregnated with the matrix and cured. The IB-sample is contained several thousand filaments of the fiber. It is basically a single-layer unidirectional fiber-reinforced composite.

Figure 1 shows a scheme of an IB-sample and distribution of the arising tensile force \( P' \) forces in the sample upon impact by force \( P \) with velocity \( v \). The sample is represented as a rod with gauge length \( L \) and diameter \( d \) with two clamps with the length \( l \) on both sides. The clamps are used to fix the sample rigidly and to provide a constant distance \( L \) between them upon impact.

![Figure 1](image_url)

**Figure 1.** Scheme of a IB-sample and distribution of the forces upon impact, where: \( L \) - length of the working part of the sample; \( d \) - diameter of the sample; \( l \) - length of the sample fixation in impact testing machine; \( \Delta \) - sample deflection at the failure point; \( P \) - force of impact; \( P' \) - tensile and breaking force; \( \gamma \) - angle between the direction of \( P \) and \( P' \) forces.
The IB-samples were obtained by longitudinal hand lay-up and impregnated with the matrix, and cured. Experiments under impact and static loading conditions were carried out by the same samples in the form of a rod with the following dimensions: \( L = 68 \text{ mm}, \ l = 24 \text{ mm}, \ d = 2.3 \text{ mm} \) (see figure 1). The samples consisted of 50 % matrix and 50 % of the fibers.

Impact is applied in the middle of the sample across the fibers. Due to the transversal impact the sample is stretched and bended by an amount \( \Delta \) above which the fibers are broken at the bending location. When the sample of CM was broken and the fibers were destroyed, their ends remained fixed in the composite.

The longitudinal deformation \( X \) and relative deformation (strain) \( \varepsilon \) (%) of the sample were calculated by the formulas (1) and (2), respectively:

\[
X = 2 \times \left( \frac{1}{2} \left( \frac{L}{2} + \frac{L}{2} \right) \right),
\]

\[
\varepsilon = \frac{X}{L}.
\]

The tensile and breakdown force \( P' \) simultaneously was calculated on the basis of forces distribution scheme (see figure 1) by the formula (3):

\[
P' = \frac{P}{2 \cos \gamma},
\]

where \( P' \) is the tensile and breakdown force, \( \gamma \) is the angle between the direction of action the forces \( P \) and \( P' \).

Ultimate breaking-down stress \( \sigma \) was calculated by the formula (4):

\[
\sigma = \frac{P'}{S},
\]

where \( S \) is the cross-sectional area of the sample.

The specific absorbed-in-fracture energy \( \alpha \) as under dynamic and static loading conditions was found from the formula (5):

\[
\alpha = \frac{W}{S},
\]

where \( W \) is the absorbed-in-fracture energy.

The shear strength \( \tau \) was calculated by the formula (6):

\[
\tau = \frac{P''}{F},
\]

where \( F \) is the surface area of the sample in clamp with the length \( l \), and \( P'' \) is the force necessary for pulling a fiber out of the matrix. The pull-out force \( P'' \) was calculated by the formula (7):

\[
P'' = \sqrt{(P')^2 - P^2}.
\]

The absorbed-in-fracture energy is the ability of a material to absorb energy to the point of break (failure). This energy characteristic is greatly dependent on the manner in which the load is applied. In the case of a dynamic situation, the value of \( W \) may be evaluated by the amount of energy absorbed during impact until sample break. The smaller the area under pendulum machine curve recorded, the less the absorbed-in-fracture energy under dynamic loading conditions.

In a static situation, the value of \( W \) may be evaluated by the area under the stress – strain (in this case load – flexure) curve up to the point of fracture (break) produced by a tensile test. The larger the area under Instron curve recorded, the greater the absorbed-in-fracture energy under static loading conditions. The value of specific absorbed-in-fracture energy \( \alpha \) may be evaluated by the amount of energy absorbed according to the cross-sectional area of broken sample in the case of a static and a dynamic situations.
Therefore, the IB test allows one to analyze mechanisms of CM loading and failure and to determine the following properties: $P$ - the loading force; $P'$ - the tensile and breakdown force simultaneously; $v$ - the loading velocity; $X$ - the longitudinal deformation; $\varepsilon$ - the relative deformation; $\Delta$ - the transverse deformation of the sample at the load location; $\sigma$ - the ultimate tensile strength; $W$ - absorbed-in-fracture energy; $\alpha$ - specific absorbed-in-fracture energy; $\tau$ - the shear strength of the fiber to the matrix [7-9].

As reinforcement we used various style of high-strength high-modulus fiber: brittle carbon fiber of trademark Tenax® – J HTA40 E13 3K 200 tex supplied by Teijin Limited (Japan) and para-aramid fiber of trademark Armos® from Teksma (Russia). The carbon fiber had strength of 4.18 GPa and an elastic modulus of 236 GPa, an elongation at break of 1.77%. The aramid fiber had strength of 5 GPa and an elastic modulus of 140 GPa, an elongation at break of 3.5%.

Polymer composition based on an HT2 epoxy resin from Poxy-Systems® with HT2 as a curing agent served as the matrix. Processing time of the matrix was 45 minutes. Mixing ratio was 100:48 parts by weight of resin to hardener. Poxy-Systems® is a registered trademark of R&G (Germany).

Five samples of each material were tested at room temperature under impact and static loading conditions, respectively. The strength and energy criteria of the FRP were obtained from the experimental load-flexure curves. Experimental results are given in the table and the figures 2 and 3.

3. Results and discussion

The effect of loading velocity on the mechanical properties and failure mechanisms of carbon fiber reinforced plastic (CFRP) and organic fiber reinforced plastic (OFRP) has been determined experimentally by IB method. Increase the loading velocity by a factor of ~ $10^4$ from $8.5 \times 10^{-5}$ m/s to 5.25 m/s results in a change as the failure mode (figures 2 and 3) and the properties (see the table) of CFRP and OFRP. The relaxation of the stresses in CM and the energy dissipation are limited the short duration of impact value equal to 1-2 ms, which caused a sharp change of CM failure mechanism under impact loading conditions as compared to static ones.

In a static situation, the deformation of CM is mostly stretching deformation. It was observed the deformation gradually grows as the load increases under static loading conditions (see curves 2 in the figures 2 and 3).

![Strain diagram (load vs flexure) for CFRP reinforced with carbon fiber Tenax® under impact 1 and static 2 loading conditions.](image)
The deformation continues up to the point where the depletion of the fiber strength is occurred. It provides the high properties of CM under static loading conditions. It is clearly seen that these curves 2 are smooth without peaks from the filament ruptures of the fiber. That way, the failure mechanism of CM under impact loading conditions differs from that under static ones [5-7].

In a dynamic situation, CM destruction was observed at the first moment of a shock load application. It occurs due to the rupture of the most loaded filaments. The entire deformation of the CM up to the point where its destruction observed was accompanied the filament ruptures of the fibers. The load fluctuations were reflected on the curves in the form of the peaks. Curves 1 in the figures 2 and 3 upon impact had a shape of a jagged saw.

Deformation under impact is composed of two sources: a multi-stage tensile deformation of the fibers, and a multi-stage deformation under stress-wave propagation, which is caused multi-breaking and crushing of the filaments. A multi-stage tensile deformation looks like in the form of horizontal segments of deformation on the diagram at a constant stresses. Deformation from stretching upon impact is become of stepwise with horizontal deformation segments on the curve at a constant load. Every such segment is finished up with a lift to a higher level of stresses as result of the accumulation of the stretching deformation. Then the process is repeated. The processes of multi-breaking and crushing filaments are imposed on the process of multi-stage stretching deformation. Due to accumulation of the crushes and breaks of the filaments the CM strength and deformation are reduced, which resulted in reduced energy criteria upon impact.

The combination of hard and brittle carbon fiber with a rigid epoxy matrix in CM is provided the highest number of breaks under impact loading (see curves 1 in the figures 2). Consequently, the process of destruction of CFRP upon impact is occurred due to the accumulation of the strain from passing waves of the stresses from impact and from multi-breaking and crushing of the filaments.

As can be clearly seen from the fracture diagrams, a great change in the properties of materials at the transition from static to impact loading conditions exhibited both brittle CFRP (figure 2), and more flex OFRP (figure 3). The destruction of OFRP upon impact was mainly occurred due to the accumulation of the deformation according to multi-stage mechanism of tensile deformation and multi-breaking filaments. A splash of the load fluctuations up to ~ 250 N was caused the ruptures of the fibers before the CM failure.

Figure 3. Strain diagram (load vs flexure) for OFRP reinforced with aramid fiber Armos® under impact 1 and static 2 loading conditions.
The main properties of CFRP and OFRP plastics are sharply reduced under impact loading conditions (see the table). Deformation capacity of CFRP and OFRP are decreased by factors of 4.5 (from 2.1 to 0.47%) and 3.2 (from 2.8 to 0.87%), respectively. Ultimate tensile strength $\sigma$ of OFRP is negligible decreased by factors of 1.4 (from 1025 to 735 MPa). The shear strength $\tau$ of OFRP is decreased by a factor of 1.4 (from 25 to 18 MPa). Specific absorbed-in-fracture energy $\alpha$ of CFRP and OFRP are significantly reduced by factors of 3.7 (from 52 to 14 J/cm$^2$) and 3.2 (from 126 to 40 J/cm$^2$), respectively.

**Table.** Main properties of CFRP and OFRP based on the epoxy matrix under static and impact loading conditions.

| CM properties | Loading conditions | Impact | Static |
|---------------|--------------------|--------|--------|
| Fiber         | Fiber              | Carbon | Armos  | Carbon | Armos |
| $\varepsilon$, % | Carbon             | 0.47   | 0.87   | 2.1    | 2.8   |
| $\sigma$, MPa | Armos              | 448    | 735    | 448    | 1025  |
| $\alpha$, J/cm$^2$ | Carbon          | 14     | 40     | 52     | 126   |
| $\tau$, MPa | Armos              | 11     | 18     | 11     | 25    |

### 4. Conclusion

The properties and failure mechanisms of anisotropic polymer composite materials reinforced with carbon and aramid fibers under impact and static loading conditions are investigated by Impact Break method. It was found out that velocity of loading strongly influences as failure mechanisms and the properties of CM. Increase the loading velocity by a factor of $\sim 10^4$ from $8.5 \times 10^{-5}$ m/s to 5.25 m/s results in a change as the failure mode and the properties of the CM. The relaxation of the stresses in CM and the energy dissipation from breaking filaments of the fiber are limited the short duration of impact value equal to 1-2 ms.

In a dynamic situation, CM destruction was observed at the first moment of a shock load application. It occurs due to the rupture of the most loaded filaments. The destruction processes in dynamically loaded CM are multi-stage. Failure mechanism is based on the multifilament fiber stretching and stress-wave propagation through the CM. The processes of multi-breaking and crushing of the filaments are imposed on the process of multi-stage stretching deformation. It led to a sharp decrease of the CM properties upon impact as compared with that CM tested under static loading conditions.

The accumulation of the crushes and breaks of the filaments was reduced the CM strength upon impact. It led to its rapid failure at smaller deformation than in a static situation. The reduction of the CM strength and deformation was resulted in a significant decrease its absorbed-in-fracture energy under impact loading conditions.

In a static situation, the deformation of CM is mostly stretching deformation. It gradually grows as the load increases. The deformation continues up to the point where the depletion of the fiber strength is occurred. It provides the high properties of CM under static loading conditions.

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A great change in the properties of materials at the transition from static to impact exhibited both brittle CFRP and more flex OFRP. The values of relative deformation, ultimate tensile strength, shear strength and specific absorbed-in-fracture energy were obtained due to IB test results for CFRP and OFRP. It has been found out that specific absorbed-in-fracture energy of CFRP and OFRP under
impact loading conditions reduced by factors of 3.7 and 3.2, respectively, and relative deformation decreased by factors of 4.5 and 3.2, as compared with that under static ones.

In summary the choice of CM to create structures based only on the static properties of the material does not guarantee the impact resistance of structures upon low-velocity impact.

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5. References

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