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To cite this article: I N Shardakov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **581** 012030

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The Study of Impact Loading on GFRP Plates Using a Network of Piezoceramic Sensors

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Abstract. Structures made of multilayered composite materials are designed to work under different types of external loads, both static and dynamic. Often, under dynamic impact, material failure occurs in the inner layers of the material and is not noticeable during external visual inspection. Untimely detection of such damage may lead to a complete failure of the structure. Therefore, the substantial problem in the control of objects made of laminated composite materials is the determination of various characteristics of external dynamic impact, which will allow to estimate the danger of an impact and localize the damage in the structure. The object of this study is a multilayered plate made of fiberglass composite, subjected to impact loads of different energy. This paper investigates material failure after an impact load and the sensitivity of a network of piezoelectric sensors to external dynamic loading.

1. Introduction

The use of polymer composite materials can significantly reduce the weight of the designed structures while maintaining the necessary performance characteristics. Nowadays safety requirements intensify at all stages of the production and operation of the designed objects, which, in turn, requires monitoring of the mechanical state of the structure during its operation to evaluate its working life. The question of correct selection of monitoring methods [1] of the mechanical state of an object in real time is extremely popular these days. The use of effective monitoring systems allows to identify defects at an early stage of their occurrence and to assess their severity, thereby preventing breakages and dangerous accidents. Various methods are used to identify defects in products, among which methods of non-destructive evaluation have gained particular popularity. Methods of non-destructive evaluation intended for the detection, localization and classification of defects include visual inspection [2]; optical methods [3]; ultrasound testing [4]; acoustic emission [5]; vibration analysis [6,7]; radiography and thermography [8,9].

However, none of the existing approaches is universal. The need for a deeper study of both the methods themselves and the possibility of combining them with each other to achieve greater efficiency opens up new prospects for improving monitoring systems, thereby increasing the level of evaluation of the mechanical state of a structure without taking it out of service.

One of the most promising is the vibrational approach. Such methods use vibrational processes excited and measured in the structure to detect damage. When developing such monitoring systems, piezoelectric elements are widely used, thanks to the direct and reverse piezoelectric effects, which allow both, to excite oscillations, that is, to act as an actuator, and to record the response of the system to external influences.



There are many scientific studies on the problems related to the development of monitoring system among which are: finding the best location for the piezoelectric sensor on the object under study for reliable detection of defects [10], issues of numerical simulation of wave propagation and its interaction with damage area [11], signal processing methods [12] and detection of location and size of the defects [13]. That is why the study of various aspects of developing a monitoring system, which allows evaluating the mechanical state of products made of different types of materials, is a crucial task.

It is well known that among the most dangerous types of external loadings are impacts which often cause severe damage of the structure. The distinctive feature of such external influence is that under impact loading (usually under low velocity impacts) an internal damage can occur which cannot be detected on the surface of an object. Constructions made from composite materials are especially vulnerable to this type of damage due to the layered structure.

In this paper, the effect of dynamic loading on multilayered composite plates made of fiberglass material in a wide range of impactor speeds (6-109 m/s) was investigated. The designed and manufactured experimental facilities, which allow reaching such speed range of external loading, are described. The analysis of damage types which appear in the composite material at the considered impact speeds was carried out. A system of dynamic response measurement using a network of piezoceramic sensors, which allows recording the response of a structure in a synchronized mode of operation, was experimentally implemented. Such system can be used as a foundation for building monitoring system which allows to detect and localize impact and identify possible occurrence of defects.

2. Description of impact loading experiments

2.1. Object of study

The object of this study is a multilayered plate made of fiberglass material, subjected to impact loads of different energy. In the experiments, square plates made from glass fiber reinforced polymer (GFRP) with a size of 500×500×4 mm and consisting of 20 layers in thickness (Figure 1) were used. According to the diagram in Figure 2, 6 piezoelectric sensors are glued to the surface of the plate. The sensors are located around a circle with a radius of 160 mm and measure the response of the system to external dynamic loading.

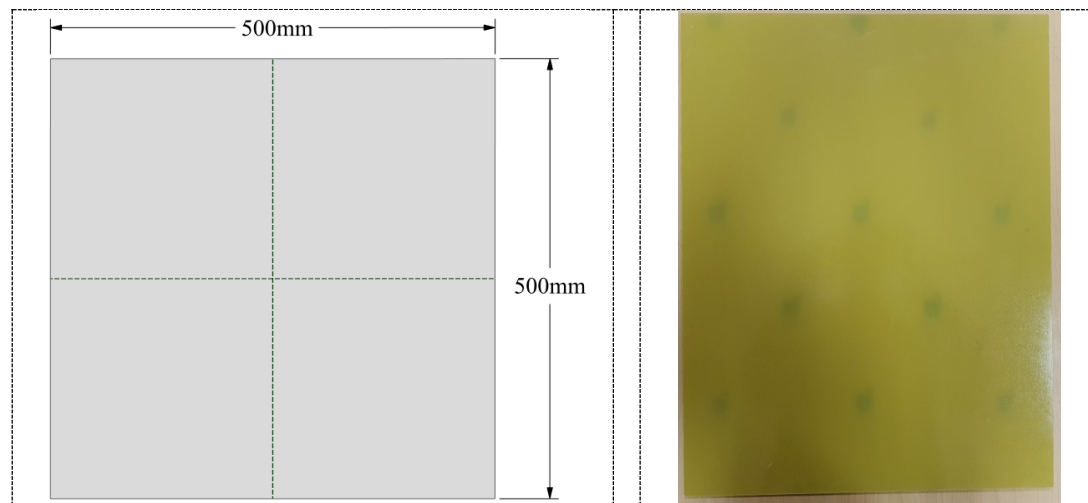
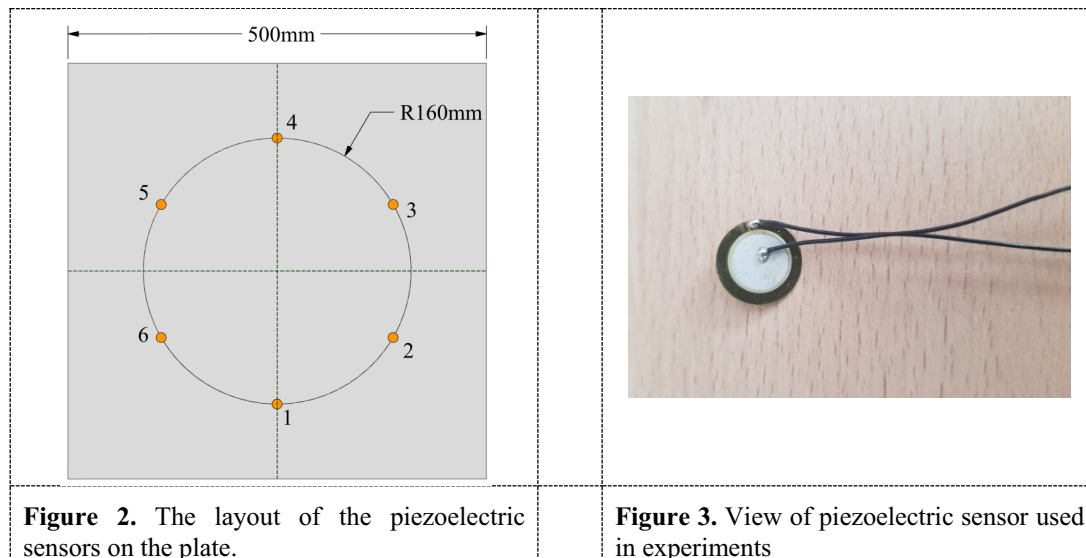


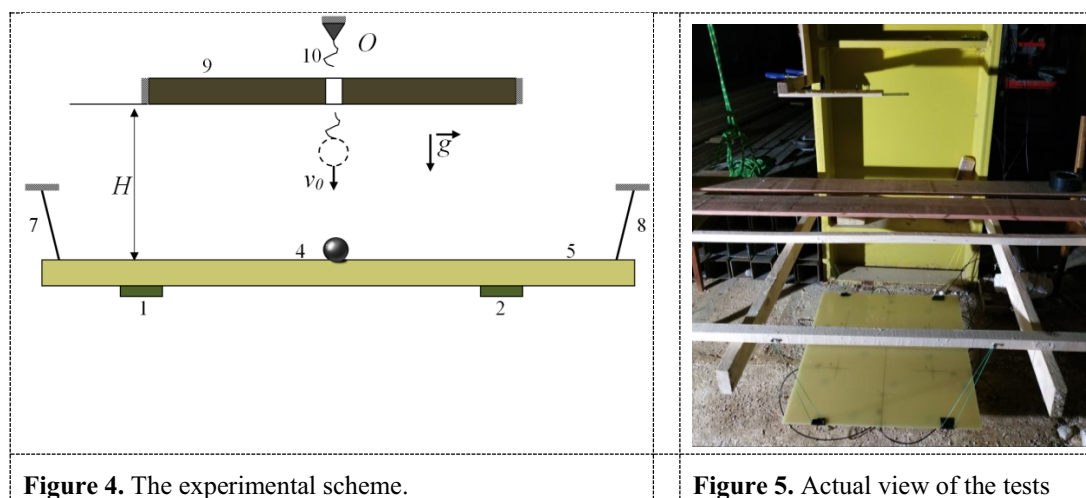
Figure 1. Plate layout (left) and photograph of GFRP plate.

Each sensor represents a piezo-ceramic on a metal substrate with attached electrodes, respectively, on the substrate and on the electro-plated surface of the piezo-ceramic (Figure 3). The diameter of the substrate is 12 mm, the diameter of piezoelectric ceramics is 9 mm, the total thickness of the sensor with the substrate is 0.21 mm, and the thickness of a single piezoceramics is 0.1 mm. A steel ball with a diameter of 25.4 mm and a weight of 66.5 g was used as an impactor



2.2. Description of impact loading experiments

In the course of the study, experiments on applying a localized impact load to the sample were carried out. The tests were performed in two ranges of impactor speeds: from 6–13 m/s and speeds in the range of 29–109 m/s. These ranges correspond to 2 different test schemes. In the first velocity range, the impact load was carried out by a metal ball with given values of radius r and mass m falling in the gravity field. In accordance with the experimental scheme of Figure 4, the ball (4) is suspended to the point O by means of an inextensible thread (10). The ball is positioned in relation to the plate by means of a hole in the bracket (9). The distance H is determined by the relative position of the bracket and the plate (5). The plate is suspended on elastic, flexible filaments (7,8) at the four corner points of the plate. The plate is located in the horizontal plane (perpendicular to the direction of the field of gravity). The ball begins to move by cutting the thread (10). The positioning of the bracket with respect to the plate in the horizontal plane was carried out using a laser level GSL Professional BOSCH. Piezoelectric sensors (1, 2) are fixed to the bottom of the plate. After cutting the thread (10), the ball flies at a speed v_0 under the action of the field of gravity and hits the plate. The experimental scheme and the actual view of the tests are presented in Figures 4 and 5.



To achieve higher impactor speeds, a pneumatic gun was used. The block diagram of this type of test is shown in Figure 6, where 1 is a compressor, 2 is an accumulation chamber, 3 is a crane, 4 is a ball, 5 is

a barrel, 6, 7 are lasers, 8, 9 are photodiodes, 10 is a catcher, 11 - test specimen, 12 - stopping unit, 13 - sample fastening.

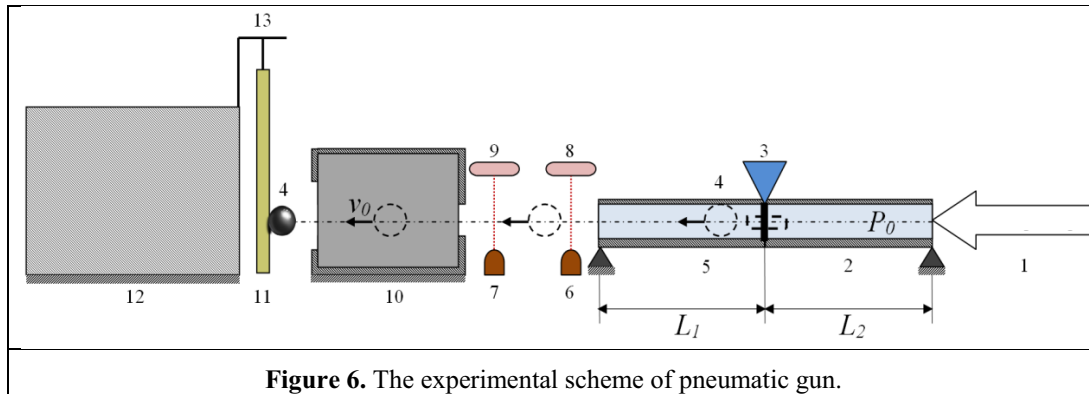


Figure 6. The experimental scheme of pneumatic gun.

In accordance with the scheme on Figure 6, the plate (11) was fixed in the bracket (13). Next the positioning of the plate (11) was carried out in order to ensure that the impactor hit the given point. The crane (3) was closed. The ball (4) was set in the barrel (5) before touching the crane (3). The required level of pressure in the chamber (2) was pumped which provides a set value of the velocity at the outlet of the barrel (5). After that the recording equipment should be turned on and the valve (3) opened to release the pressure and push the ball.

2.3. Impact loading in the speed range of 6-13 m/s

Impact loading in the speed range of 6-13 m/s, with the help of a metal ball falling in the field of gravity, corresponds to a height interval of 1.9 - 8.6 m. The tests were carried out according to the scheme in Figure 4. An individual point on the composite plate corresponded to each impactor speed. The marking of impact points on the plate is presented in Figure 7. The distance between the points is 10 mm. Data on the experiments is presented in Table 1

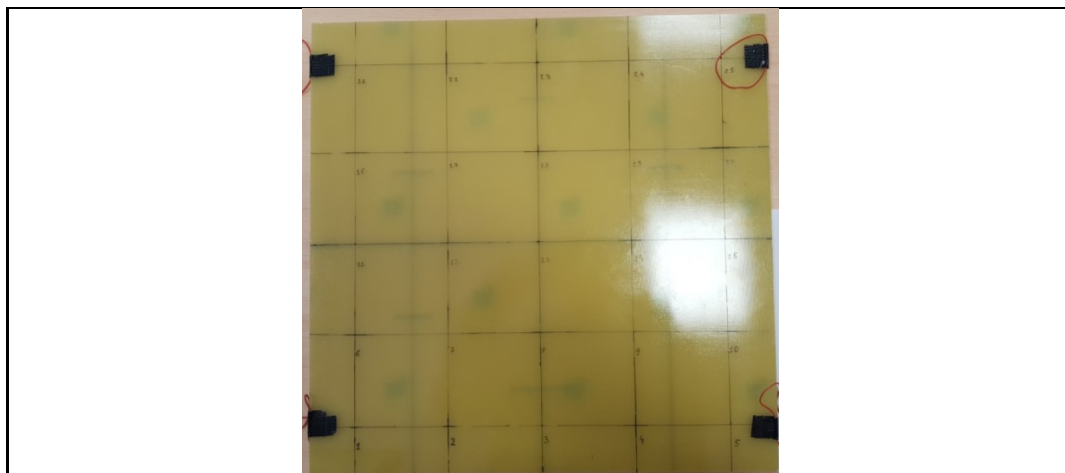
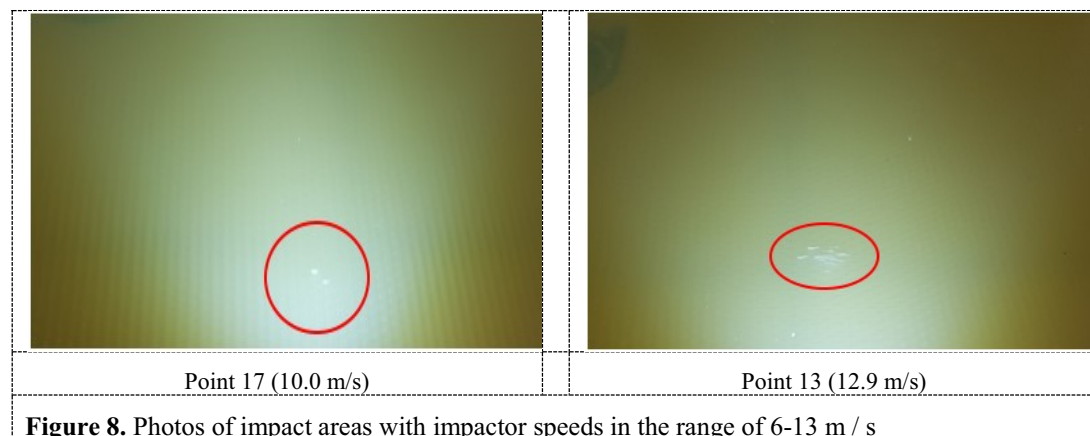


Figure 7. Layout of the plate during impact tests using a metal ball falling in the gravity field

Table 1. Experimental data on impact loading in the speed range of 6-13 m/s, using a metal ball falling in the field of gravity.

height (m)	velocity (m/s)	Point number
1.925	6.1	11
3.395	8.2	12
4.267	9.2	7
5.073	10.0	17
5.857	10.7	9
6.651	11.4	14
7.443	12.1	19
8.520	12.9	13

After the impact tests, a plate was visually inspected for damage. Photographs of impact areas where the damage is visually recognizable are presented in Figure 8.

**Figure 8.** Photos of impact areas with impactor speeds in the range of 6-13 m / s

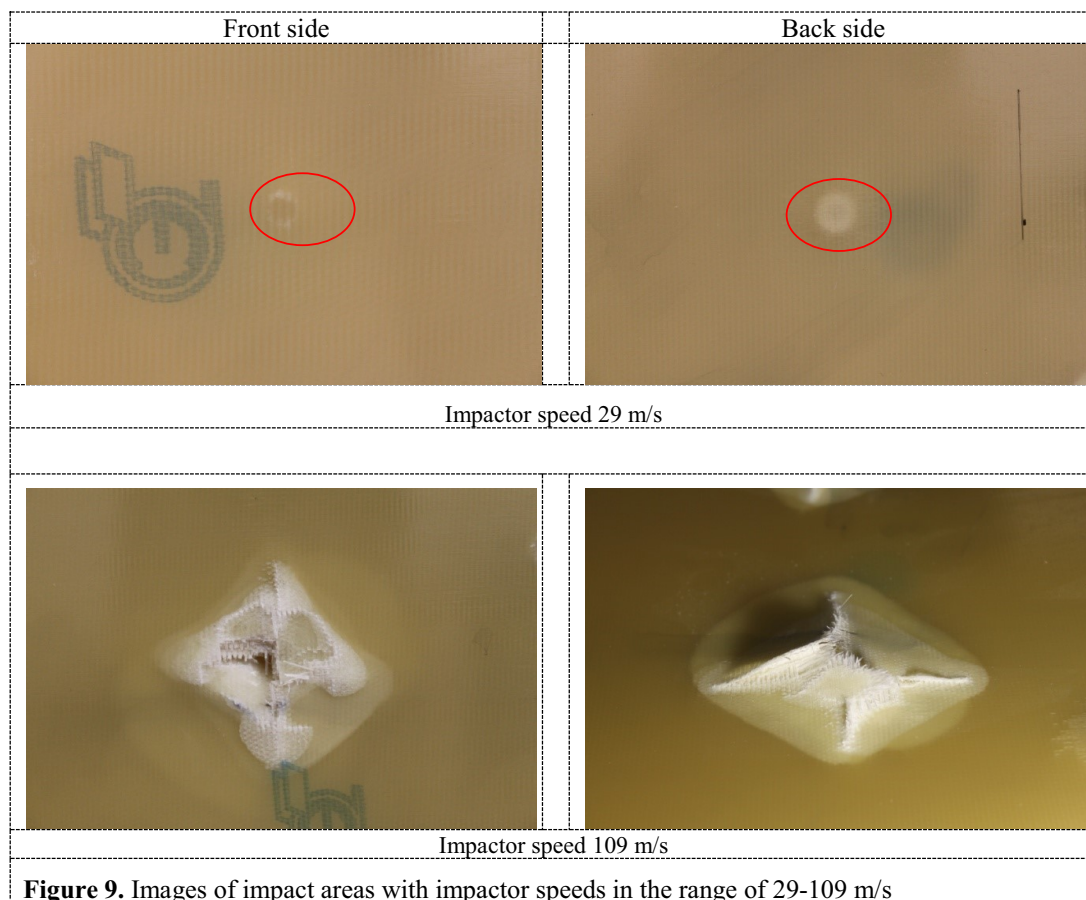
The first visually noticeable damage is detected upon impact at a speed of 10 m/s. The damage area increases with the speed of the impactor. The size of the maximum visually detected defect is 8.3×4.8 mm. All visually detected damages are characterized by slight cracking in the local area from the side opposite to the impact.

2.4. Impact loading in the speed range of 29-109 m/s

A series of impact tests was carried out with the impactor speed range of 29-109 m/s using a pneumatic gun. Data on the speeds of individual tests and the size of the visually discernible damages are presented in Table 2. Photographs on both sides of the plate for some tests are shown in Figure 9.

Table 2. Experimental data on impact loading in the speed range of 29-109 m/s.

velocity (m/s)	Diameter of damage area, mm
29	8
43	11
54	35
69	36
85	68
109	78



In the considered speed range of the impactor, the damage on the plate is easily identified visually. Starting at 54 m/s, the threads of reinforcement of the composite material break in the form of a cross. In addition to breaking of the reinforcement filaments, zones of internal delamination and the area of cracking of the matrix are observed. At the last test at a speed of 109 m/s, a plate was pierced by the impactor.

3. Registration of impact loading by a network of piezoelectric sensors

As part of this work, a system for recording elastic waves arising from the interaction of an impactor and a plate was developed and constructed. It consists of 6 synchronized channels, which provide registration of vibrations at 6 points with the help of piezoceramic sensors. The registration of electrical signals from sensors during impact at various points of the plate and at different speeds of the impactor was performed.

A series of experiments of throwing a spherical weight from a height of 767 mm onto a plate, at the points of location of the piezoelectric sensors, but from the opposite side of the plate was carried out. The resulting signals demonstrate the greatest response of those sensors to the coordinates of which the impact was made. Figure 10 shows the signals of sensors 1 and 2 under impacts at corresponding points on the plate.

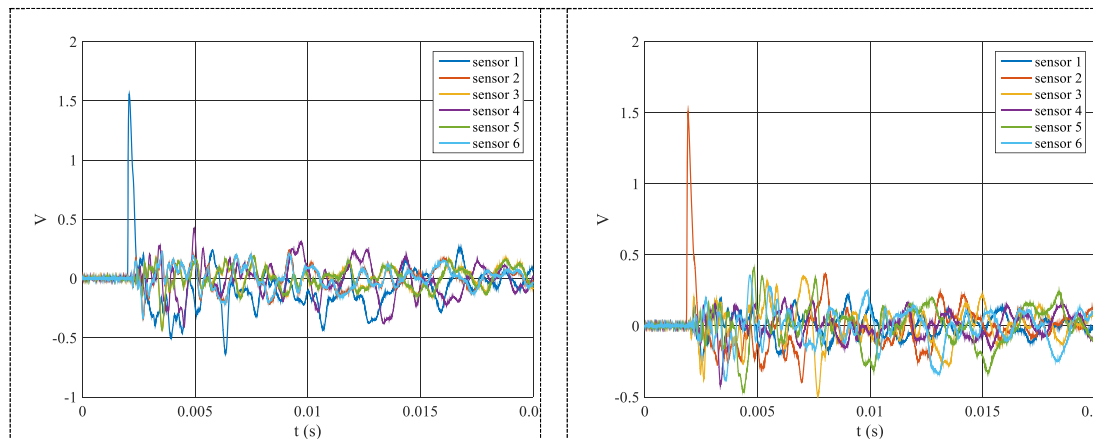


Figure 10. Sensor response upon impact at the location of piezoelectric elements.

Similarly, an impact was made to the center of the plate with the signals recorded by all the sensors (Figure 11). The received responses demonstrate the synchronous behavior of sensors 2, 3, 5, 6 and some shift of signals from sensors 1 and 2, which is clearly visible in the initial area of the graph in Figure 12.

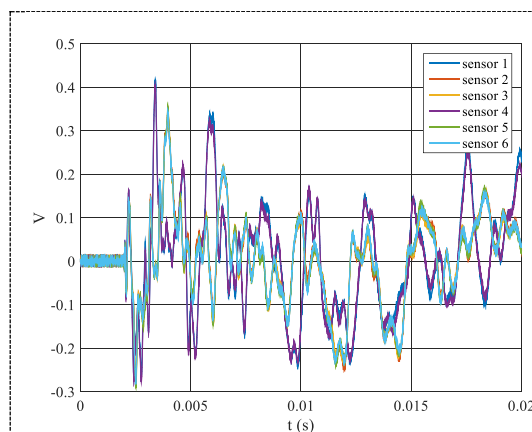


Figure 11. The response of the sensors upon impact to the center of the plate.

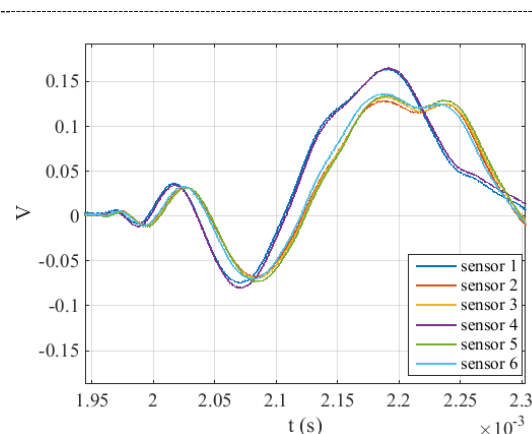


Figure 12. The initial area of the signals from piezoelectric sensors upon impact to the center of the plate.

4. Conclusions

In this work, the impact velocity leading to the formation of primary defects in the form of cracking of the matrix on the back surface of a fiberglass laminate was determined. Which is 10 m/s. With further increase in speed, the cracking area increases. Experimental setup for testing composite plates on the impact of a spherical body at high impactor speeds (29-109 m/s) was designed and tested. The following patterns were found with increasing of impactor speed. At speeds from 29 to 43 m/s, a significant increase in the area of matrix destruction throughout the entire thickness of the plate is observed. Starting at 54 m/s, the threads of reinforcement of the composite material break and form the shape of a cross. At speeds of the impactor over 109 m/s, the impactor goes through the plates. A system of elastic waves measurement resulting from the interaction of an impactor and a plate was developed. It consists of 6 synchronized channels, which provide registration of vibrations at 6 points of object under study.

The registration of electrical signals from piezoceramic sensors under impact loadings at various points of the plate and at different speeds of the impactor was performed which confirmed the sensitivity of developed system.

Acknowledgments

The results were obtained within the framework of the state task of Russian Ministry of Education and Science (project no. 11.2391.2017/4.6).

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