

Experimental research of energy absorbing structures within helmet samples made with the additive manufacturing method – preliminary study

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Purpose: This study aimed to develop an energy-absorbing structure for bicycle helmets to minimize head injuries caused by collisions. The research team explored three geometric structures produced through additive methods and compares their energy absorption properties with a standard bicycle helmet made of Expanded Polystyrene (EPS) foam. *Methods:* The study prepared samples of three geometric structures (a ball, a honeycomb and a conical shape) and a fragment of a bicycle helmet made of EPS foam with the same overall dimensions. Laboratory tests were conducted using a pneumatic hammer, piston compressor, anvil, triaxial accelerometer and data processing systems. Three crash tests were performed for each type of structure, and the anvil's maximum acceleration and stopping distance after the crash were analyzed. *Results:* The study found that the energy absorption properties of the Polylactic Acid (PLA) material printed with the incremental method were comparable or better than those of the EPS material used in helmets. The geometric structure of the energy-absorbing material played a crucial role in its effectiveness. The most promising results were obtained for the ball samples. *Conclusions:* The study concluded that further research on energy-absorbing structures made using the Fused Deposition Modeling (FDM) method could be useful in the production of bicycle helmets. The results show that the geometric structure of the energy-absorbing material is a crucial factor in its effectiveness. The findings suggest that the ball-shaped structure made with PLA material printed using the incremental method could be a promising design for bicycle helmets to minimize head injuries caused by collisions.

Key words: energy absorbing structures, bicycle helmets, additive manufacturing, destructive testing

1. Introduction

Every year, over 40 000 cyclists are killed in road accidents. This corresponds to 3% of all road accident victims. It is worth noting that compared to cars, it is easier for the cyclist to lose balance. Moreover, in the event of a collision, the protection of the cyclist is much lower than in case of the car driver and the threat to other users is much smaller [26]. It can be proved that the head and neck are most at risk in accidents. This follows from the study covered pedestrians, cyclists, motorcyclists and car passengers in Europe [1].

In a sample of 30,000 bicycle accidents in 8 European countries, injuries on individual body parts of injuries were analyzed. Other study concluded that 37% of cyclists could survive if they were wearing a helmet [3]. Therefore, it is crucial to protect the head and, above all, to use and promote a helmet in daily commutes.

The main task of the helmet is to disperse the forces generated during an impact on the largest possible surface so that the skull suffers as little as possible. Part of the energy from the impact should be absorbed, thus reducing the acceleration acting on the brain. The helmet should fit the individual's head,

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which is ensured by a fastening system with straps. The load transferred from the head to the neck should be minimized so that the cervical vertebrae are not affected. After a collision with an obstacle, the structure of the helmet may be damaged. In this case, the helmet should be immediately replaced. Each helmet also has a specific lifetime which should not exceed 5 years. A good helmet is characterized by sufficient head ventilation and its mass. Design, workmanship and price are not without significance for the buyer.

The EN 1078+A1:2013-04 standard [27] specifies the requirements for carrying out tests on helmets for cyclists and users of skateboards and roller skates. They include the following: impact tests (tests are performed at velocity of 5.42 m/s, respectively, which correspond to drop from 1.5 m with use of flat and kerbstone anvils), strength of the retention system tests (with use of an inertial hammer suspended from the straps) and retention system stability tests (tests of helmet and retention system stability by attaching an inertial hammer of 10 kg mass and 250 mm drop height to the opposite edge of the helmet). It can be noted that the procedure for testing helmets according to the mentioned standard is much simpler to carry out than classic crash tests for a car. In that case, the risk of failure is quite high [24]. Nevertheless, it should be noted that in recent years, more advanced tests, for example simulating, a real situation of collision between a car and a bicycle have been increasingly conducted. The concept of using cyclist helmet airbags is also under development [5]. During considering issues related to the injury biomechanics in crashes, numerical simulations using the Total Human Model for Safety (THUMS) are widely used due to their low cost and easy modification of input parameters [8], [11], [15], [16], [19], [21].

It is also worth noting that the expansion of bicycle path infrastructure and reduced speed of motor vehicles in mixed traffic play a key role to improve safety. Bicycle paths physically separate cyclists from cars and reduced speeds decrease the potential for severe injury if an impact were to occur. Additionally, the driver assistance systems installed in cars, which can detect a cyclist or a pedestrian, are in developmental stage and are continually undergoing improvement [22], [23].

One measure to reduce the effects of traffic accidents may be to use energy-absorbing structures. The use of energy-absorbing materials helps dissipate kinetic energy during impact. Studies and development in this area have received attention since the 1970s [17]. The following areas of use of the structures and materials mentioned can be distinguished in traffic

safety: energy-absorbing structures used to improve vehicles' crashworthiness, structures used for highway safety (e.g., W-beam guiderail system) and structures and materials used for personal safety (e.g., bicycle helmets). In other applications, they may also be considered: structures used for protection against industrial accidents, material used for packaging [17], and also energy absorbing elements of structure for applications in Unmanned Aerial Vehicles (UAVs) [18].

Issues related to the properties and characteristics of energy-intensive materials were the subject of much research and analysis. Research about influence of a shape of energy-absorbing element from epoxy resin on energy absorption capacity was conducted [20]. The structures analyzed in this study in terms of energy absorption capacity (from highest to lowest) can be ranked as follows: elements with annular cross-section, truncated cones, flat elements in the shape of a thin cuboid and wavy cross-section, elements in the shape of a sphere. Results of tests of energy-absorbing elements of various shapes enable their proper selection for the designed energy-absorbing structure exposed to load [20]. The structure of synthetic materials specifically for energy absorption applications are often inspired by the nature – nacre, conch shell, shrimp shell, horns, hooves and beetle wings. A tool to fabricate bioinspired structures can be Additive Manufacturing – 3D printing [10]. In addition to the analysis of individual structures and shapes, the properties of individual special materials are also studied. With regard to the possible use in traditional explosion protection systems, aluminum foam, Nomex[®] honeycomb, Skydex[®] and expanded polystyrene were considered [4]. The aluminum foam was characterized as having the lowest permanent deformation.

Research and analysis related to the use of energy-absorbing materials for helmets have been conducted [6], [7], [12], [13], [25]. The conducted research shows that natural and hybrid fibers has better mechanical properties than plastic materials used for the creation of the safety helmets [6]. In another study, a numerical experiment was conducted, where the use of a special insert from Acrylonitrile Butadiene Styrene (ABS) material with semispherical cones was proposed. The helmet impacts simulation demonstrated that a helmet with a semispherical cone liner provides better protection for the human head compared to EPS foam liner [25]. The other alternative to the traditional synthetic liners is using agglomerated cork [7], [12]. It was also proven that a composite material consisting of two cork materials (agglomerated and expanded black) showed better properties. The peak force exerted on the helmet user's head during impact was by about 10% less

compared to agglomerated samples [12]. In the context of using composite materials, the arrangement of fiber orientations also plays an important role [2]. The use of Flocked Energy Absorbing Materials (FEAM) also have been under consideration. These materials have a lower ratio of Impact Force Absorbing (IFA) to Actual Density (AD) compared to foam materials like vinyl-nitrile and ethylene vinyl acetate. In the other hand, FEAM have a higher level of comfort (breathability). Liners made from a combination of these materials have been developed to achieve compromise properties [13]. The use of different types and structures of energy-consuming materials is also considered in the context of the design of various engineering devices [4], [9], [14].

An analysis of research conducted around the world shows that considerations for helmet liners were concerned with the materials used, less so with the shape of the structure. Studies [20] have considered various shapes of specimens, but not in the context of a helmet liner. Constraints based on comfort of use are important and should be considered. Moreover, another research [25] considered only one alternative structure shape and was based on computer simulation. This indicates that there is a need to systematically investigate the properties of structures with different structure shapes in the context of its ability to replace the standard helmet liner.

2. Materials and methods

Background

In order to increase the safety of vulnerable road users, it is important to identify innovative solutions for their protection. Head protection is particularly important. This was the motivation for conducting studies

related to the search for alternative structures for the construction of protective helmets. A useful and gaining popularity tool that can be applied to rapid prototyping are additive technologies, particularly 3D printing.

The purpose of conducting the tests was to study the energy absorption capacity of the samples made by the additive method. The structures of the samples had different shapes.

During the study, the following steps were assumed:

- sample preparation,
- construction of the test stand,
- planning the procedure for conducting the tests,
- conducting tests to evaluate the degree of energy absorption using dynamic destructive tests,
- analysis of the obtained results.

Sample preparation

The study included testing three types of structures: honeycomb, conical and ball samples. The samples were designed in the Siemens NX package. In each case, the overall dimensions of the sample were $15 \times 20 \times 30$ mm. The structures samples are shown in Fig. 1.

The samples were printed in FDM technology. The FDM method is an incremental method and consists of applying successive layers of thermoplastic material. The thermoplastic material used for printing is PLA (polylactic acid), a biodegradable polymer belonging to the group of aliphatic polyesters, obtained, e.g., from corn. The printing process is shown in Fig. 2.

Test stand

The test stand includes:

- pneumatic hammer with a guide (540 mm) and a limiter stand construction;
- piston compressor;

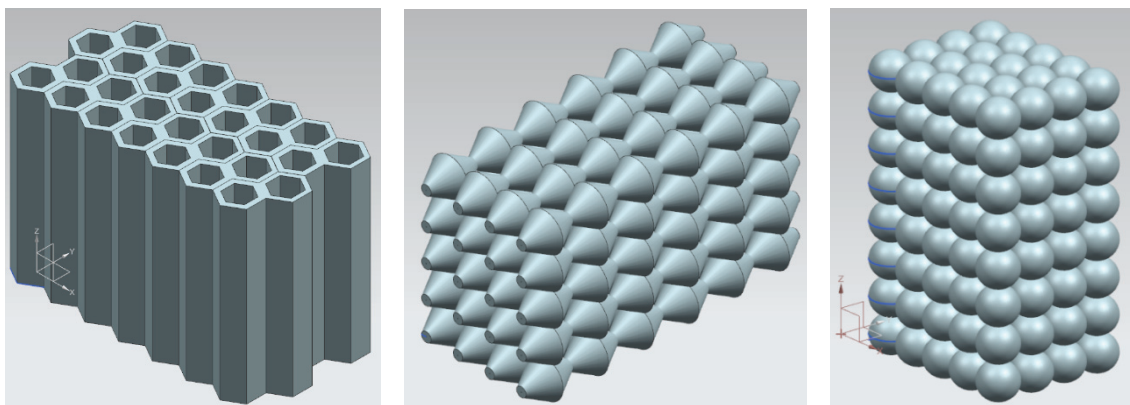


Fig. 1. Structures samples (honeycomb, conical and ball) in CAD software

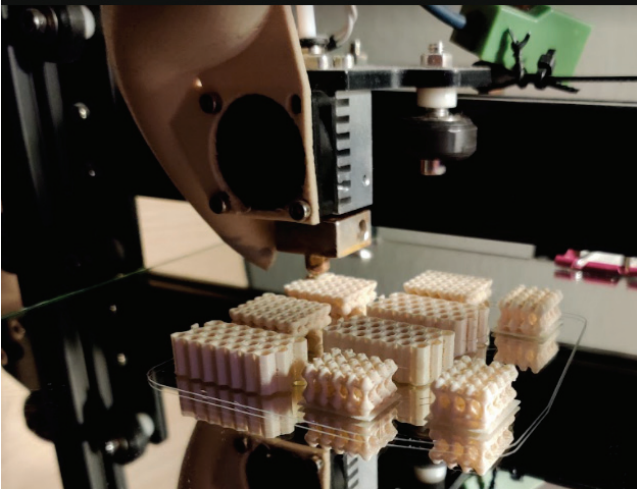


Fig. 2. FDM printing process

- anvil (1.8 kg);
- triaxial accelerometer (model 3313A1 from Dytran);
- Sirius measuring amplifier cooperating with the acceleration sensor;
- power supply;
- PC computer with Devesoft software that allows the setting accelerometer parameters along with saving and exporting data;
- HD camera built into the One Plus 7T Pro smartphone with 480 fps recording at a resolution of 1280×720 px.

The main part of test stand is shown in Fig. 3.

A pneumatic hammer welded horizontally to the guide was used for the tests. At the base of its piston, in the guide profile, there is a steel anvil with one degree of freedom of movement. The hammer is fed only with compressed air supplied by a flexible hose from a reciprocating compressor at 4 bars, with the possibility of valve adjustment. The hammer is equipped with an ergonomic trigger. After reaching the working

pressure, the user presses the trigger, which sets the piston into motion and transfers the kinetic energy to the anvil. The guide is limited by a stationary metal barrier. A sample is placed on the stopper and glued with an instant glue. For safety reasons, the test stand is protected by a transparent cover, so that during a collision, the samples do not splash in the laboratory, posing no potential hazard to the observer. The transparent bowl ensures good visibility and enables the observer to record the examination image in high resolution. In order to avoid the phenomenon of recoil after firing the piston, the stand is loaded with weights. The piston ejection and the collision of samples are very loud – exceeding 100 dB. It should be emphasized that the action is so fast that it is barely noticeable to a careful observer with the naked eye.

In the study, the Sirius analyzer was used for the Data Acquisition System, which allows for the collection of data from the acceleration sensor. Sirius is equipped with a USB port and is connected to a computer via a cable. The software compatible with this device is Devesoft. The program allows and individual to set the initial accelerometer parameters, i.e., sensitivity, sampling frequency and the option of powering the Integrated Electronics Piezo-Electric (IEPE) sensor by the amplifier. In addition, the software enables real-time recording of the test run, generation of graphs, analyzation of the peaks and exportation of data to the Excel calculation package.

The study established the required sampling frequency at 20 kHz and the sensitivity parameter at 1.

Destructive collisions of samples

In the process, twelve destructive tests of samples were performed, differing in geometric structures, volume and material (only for the helmet sample). Tests

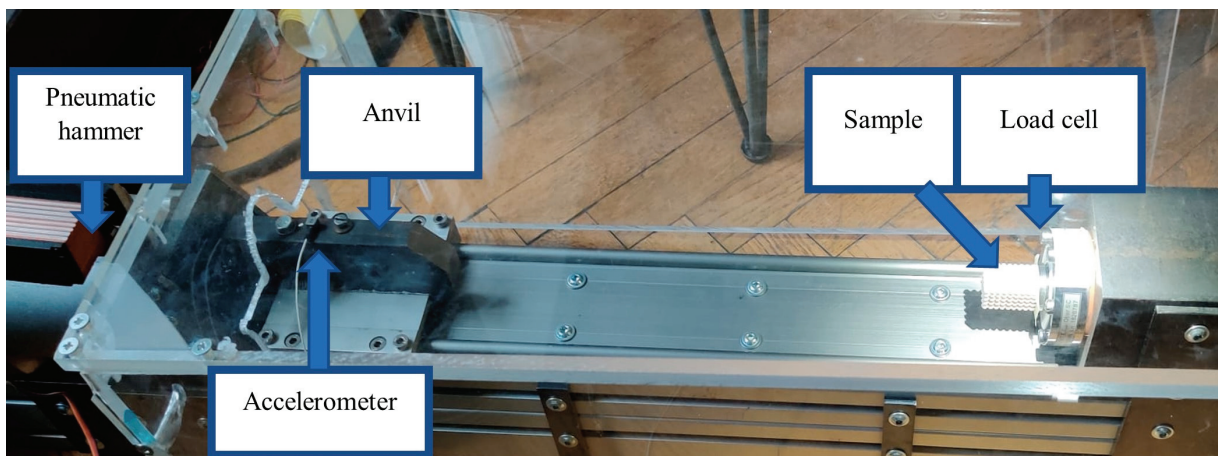


Fig. 3. Measurement station with a prepared sample



Fig. 4. The courses of destructive tests of a ball sample and an EPS sample cut from the helmet

were carried out at 20 °C with the same initial parameters:

- the speed of the anvil before the collision with the samples was the same and amounted to 7.2 m/s, the speed of the anvil was determined based on the frames from the simulation;
- the samples were placed in the same position on the barrier and at the same distance from the anvil (510 mm to the sample).

During one experiment (ball sample) there was a data writing error. As such, only the results of the

other two tests with ball samples were included in further analysis.

The courses of destructive tests of a ball sample and a sample cut from the helmet are shown in Fig. 4.

3. Result

In Figure 5, the dependence of the acceleration of the anvil during the collision with the ball samples is shown.

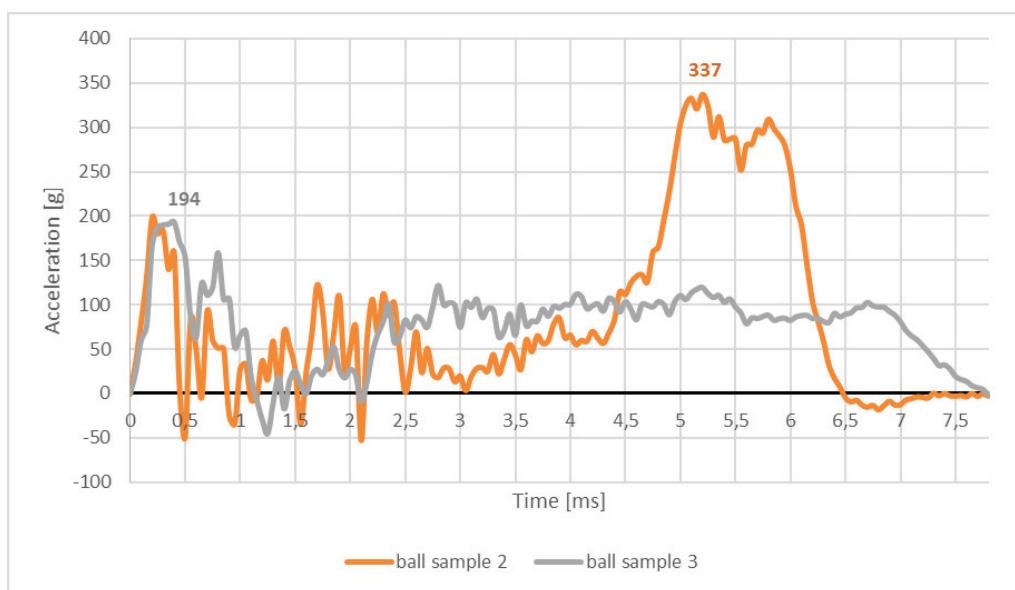


Fig. 5. Time dependence of acceleration for ball samples

For ball samples, durations of the collision were about 6.5 ms for the second sample and more than 7.5 ms for the third sample. The maximum recorded values of the acceleration peak were respectively 337 g and 194 g. During the experiment with first ball sample, there was a data writing error.

In Figure 6, the dependence of the acceleration of the anvil during the collision with the honeycomb samples is shown.

For honeycomb samples, durations of the collision were in the range of 0.8–1.0 ms for all samples. The maximum recorded values of the acceleration peak were close to 1300–1400 g for all cases.

In Figure 7, the dependence of the acceleration of the anvil during the collision with the conical samples is shown.

For conical samples, durations of the collision were close to 0.9 ms for all samples. The maximum recorded values of the acceleration peak were similar for all cases (1200–1400 g).

In Figure 8, the dependence of the acceleration of the anvil during the collision with the EPS samples is shown.

The course of the acceleration function for the EPS (helmet) sample was different from that of the prepared structure samples. The changes in accelera-

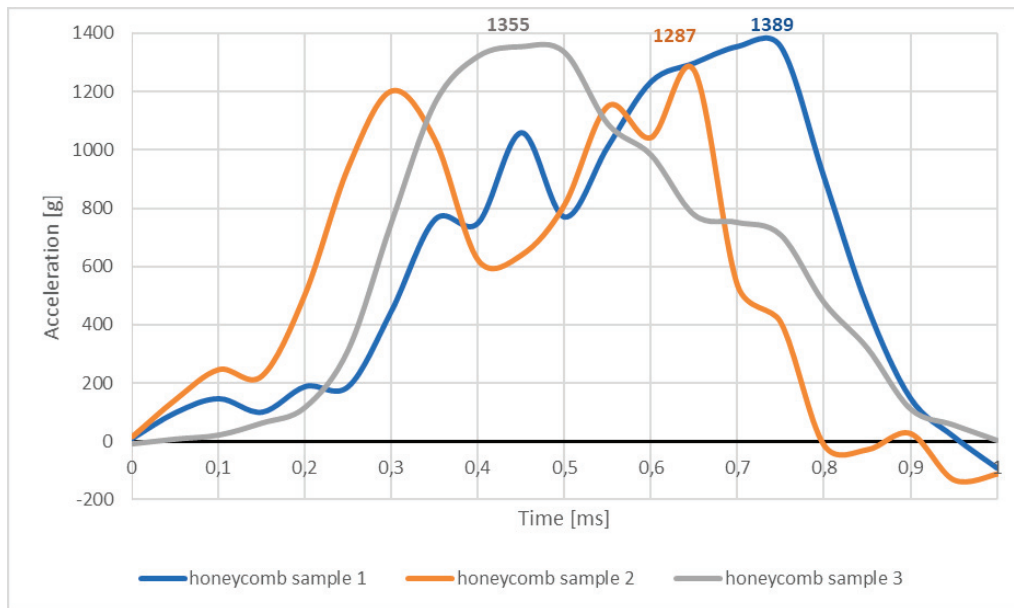


Fig. 6. Time dependence of acceleration for honeycomb samples

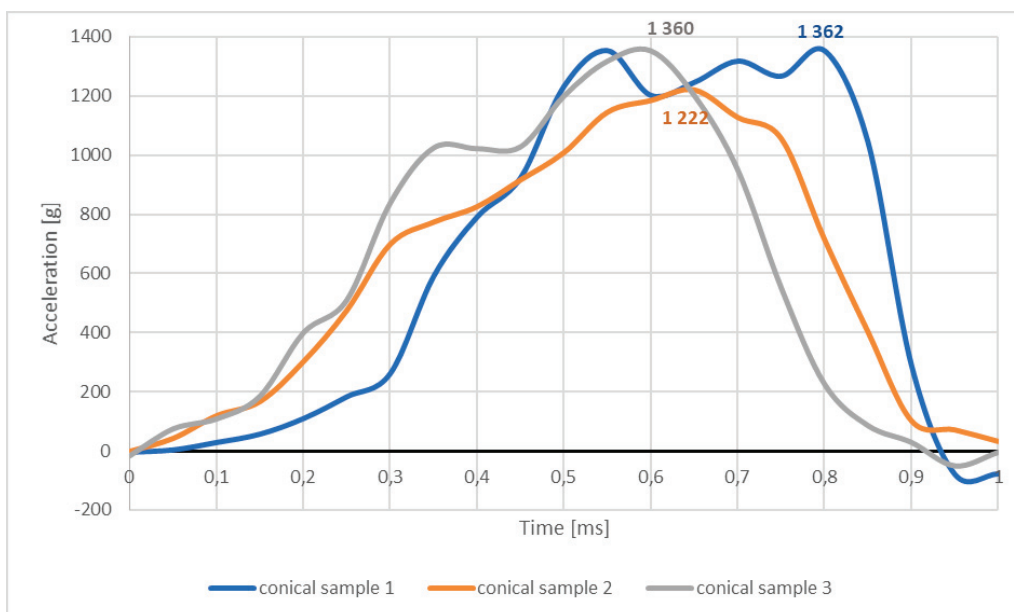


Fig. 7. Time dependence of acceleration for conical samples

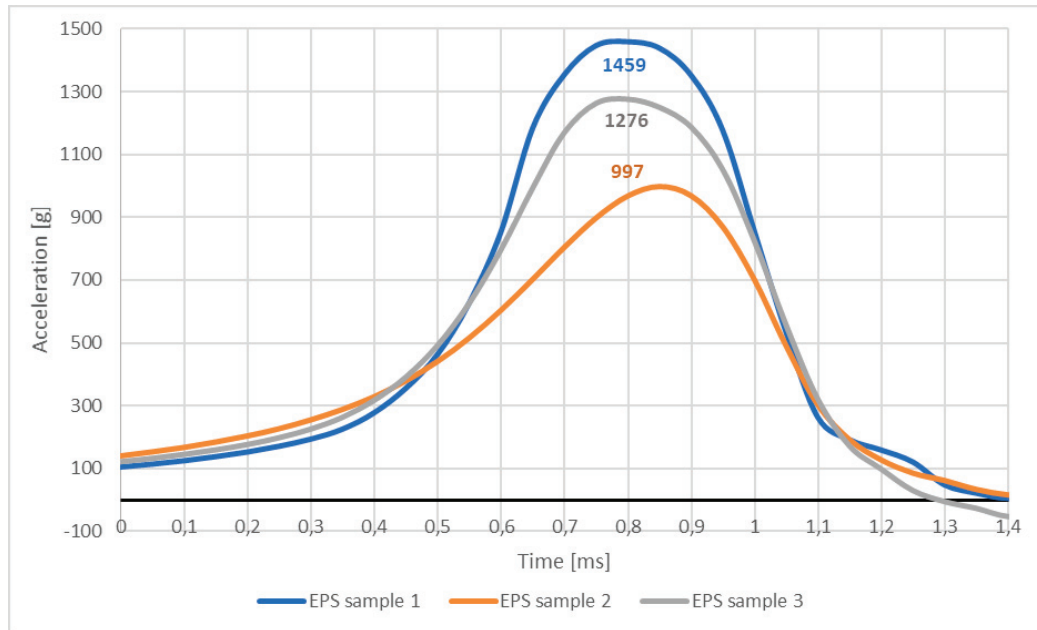


Fig. 8. Time dependence of acceleration for EPS samples

tion over time were more regular. The acceleration grew up slowly, so in Fig. 8, the values from the time the acceleration exceeded 100 g are shown. The highest acceleration value was recorded for sample 1–1459 g. The duration of the individual collisions was very similar.

In Table 1, the volume dependence of the maximum anvil acceleration and durations of collisions for all samples are shown.

Table 1. The maximum acceleration of the anvil and durations of collisions for all samples

Kind of sample	Average maximum acceleration [g]	Average duration of collision [ms]
ball	267	7.15
honeycomb	1344	0.93
conical	1315	0.91
EPS (helmet)	1244	1.37*

* For this case the average duration of collision was measured from the time the acceleration exceeded 100 g.

The highest values of accelerations were obtained for honeycomb and conical samples. For these cases, the lowest collision durations were observed. For ball samples, the maximum acceleration values were the lowest, average duration of collision was the longest.

Due to the different volume of the material used to produce the samples, the parameter of normalized maximum acceleration was determined.

The following relationship was formulated:

$$a_{\max_n} = a_{\max} \frac{v}{v_{ref}}, \tag{1}$$

where:

a_{\max_n} – normalized maximum acceleration of the sample [g],

a_{\max} – maximum acceleration of the sample [g],

v – sample structure volume [mm³],

v_{ref} – reference sample volume [mm³].

EPS sample 1 was taken as a reference. Samples volumes are presented in Table 2. The normalized maximum accelerations for all types of samples are shown in Fig. 9.

The analysis indicates that similar maximum accelerations of the anvil were achieved for honeycomb and conical samples with similar collision times. In contrast, several times lower accelerations (5 times on average) with about 8 times longer collision times were recorded for the ball samples. Consideration of the degree of samples filling (volume of used material) indicates the great potential for the use of alternative shapes, in particular ball samples. This is because similar or better properties were achieved with a smaller volume of structure (sample filling). It should be emphasized that because the density of the foam (EPS) is considerably lower than PLA, results presented in Fig. 9, between the PLA samples and the EPS (helmet) sample, cannot be compared thoughtlessly. The main goal is to indicate the best alternative structure (according to the shape criterion) among the 3D printed samples.

Table 2. Samples volumes

Type of sample	Sample dimensions	Structure volume [mm ³]		
		sample 1	sample 2	sample 3
Ball	overall dimensions: 15 × 20 × 30 mm, ball diameter: 3.8 mm, wall thickness: 1.2 mm, 160 balls in the sample		6858	6858
Honeycomb	overall dimensions: 15 × 20 × 30 mm, regular hexagonal prism (height 20 mm, base – a hexagon with an internal side of 1.6 mm and a wall thickness of 0.6mm), 28 prisms in the sample	3674	3674	3674
Conical	overall dimensions 15 × 20 × 30 mm. Cone dimensions: cone wall thickness 1.2 mm, diameter 4 mm, cone angle 60°, 120 cones in the sample	2014	2014	2014
EPS (helmet)	cuboid with overall dimensions: for sample 1: 16 × 32 × 21 mm for samples 2 and 3: 16 × 34 × 18 mm	10752 (reference)	9792	9792

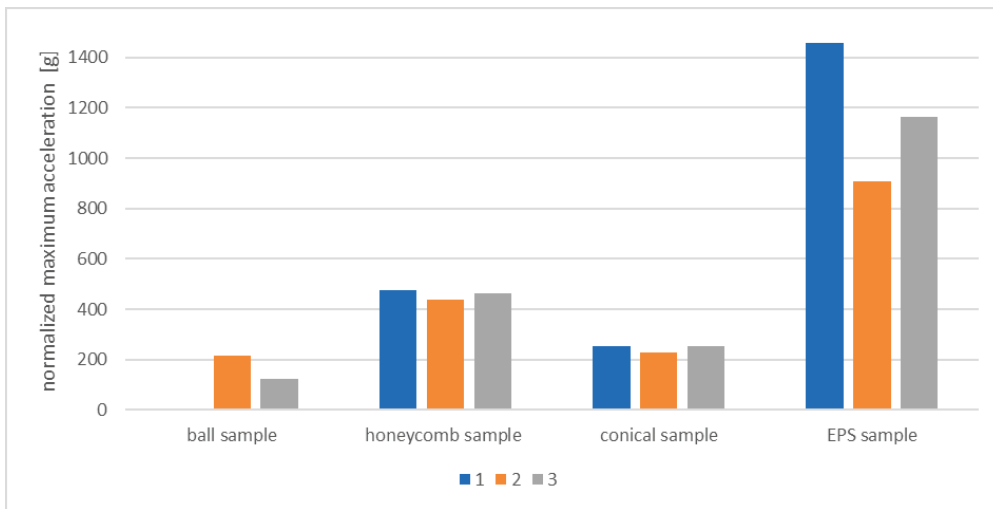


Fig. 9. Normalized maximum acceleration for all samples

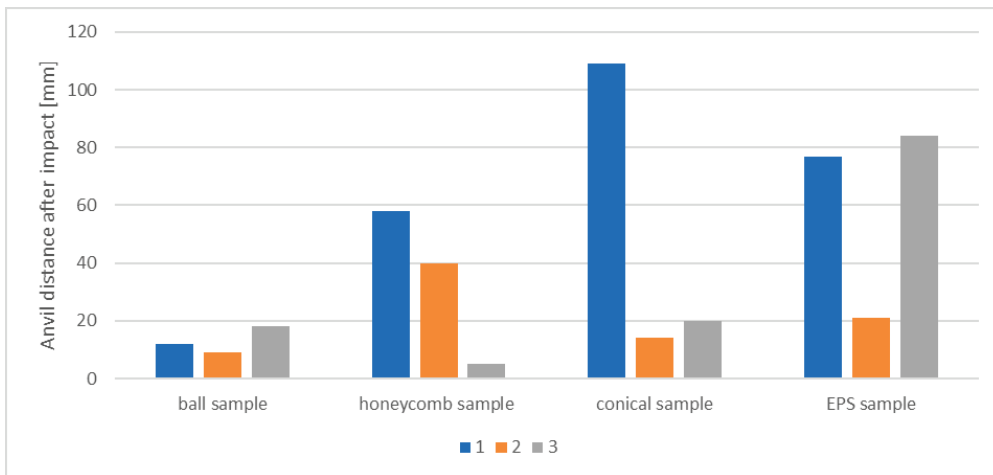


Fig. 10. Anvil distance after impact

Another parameter analyzed was anvil distance after impact with sample (distance between final position of the anvil and sample position). Results are presented in Fig. 10.

As the samples had different degrees of filling (structure volume), mass and type of structure, the interpretation of the results should consider the mentioned differences. First of all, it should be noted that

the ball structure samples guarantees the uniformity and repeatability of the results obtained. In this case, the anvil distance after impact was similar for all samples. In the cases of different samples (honeycomb, conical and helmet), the result were more varied. Considering the structure volume of sample, it can be concluded that the highest degree of energy absorption was observed for the ball sample, followed by honeycomb and conical.

4. Discussion

Alternative shapes of structures are worth considering for the use in helmet construction. The most promising results were obtained for ball samples. In this case, the maximum acceleration values were the lowest and average duration of collision was the longest. This means that with this structure, the energy absorption process will be more spread out over time, which will reflect in better cushioning during impact. In addition, the performed experiment shows that the structure of ball samples is the most efficient. For this sample, the highest degree of energy absorption was observed, considering the volume of structure.

It should also be noted that the other alternative samples of structures also showed comparable or better properties than the helmet sample. It means that structures produced by the additive technology method are alternatives worth considering to the EPS materials. These methods may be successfully applied in the production of bicycle helmets. The ability to customize the structure of these energy-absorbing materials using additive manufacturing methods offers new possibilities for optimizing helmet design. Additive technologies make it possible to achieve a very high level of variability of structures as well as the possibility of selecting different materials. However, an additional protective layer should also be provided to prevent material splashing, which would make the helmet shell rigid. Further research could determine the optimal combination of structure and protective layer to maximize energy absorption while maintaining helmet safety. It is worth emphasizing that the destructive energy obtained in the tests is several times higher than in the standardized tests, meaning the samples were completely destructed after each collision.

The preliminary nature of this study means that further research is needed to fully evaluate the effectiveness of these alternative structures in helmet design. Specifically, more comprehensive testing and evaluation are necessary to determine the long-term durabil-

ity and performance of these structures under various impact conditions. In addition, future studies should explore the potential of combining different structures to optimize energy absorption while minimizing mass and volume.

5. Conclusions

In the study, three different geometric structures (ball, conical and honeycomb) were considered and analyzed in terms of energy absorption. The data measured by the triaxial accelerometer made it possible to obtain the fields of acceleration, which made attempts to destroy the samples. From the analysis of the graphs considering the volume of samples, it was concluded that the best absorption parameters were demonstrated by the ball structure. The honeycomb structure had similarly adequate energy absorption parameters, while the conical structure had the worst absorption parameters. It should be considered that all alternative geometric structures demonstrated similar or better properties than the helmet sample. In conclusion and in the context of energy consumption, the spatial structure of the material is of primary importance.

Further research on energy absorbing structures should consist of performing tests in conditions similar to those in normalized tests. Future studies can also explore the possibility of combining different structures to increase energy absorption level and the impact of the helmet's protective layer on the performance improvement of these alternative structures. In order to map the impact as accurately as possible, the entire helmet shell should also be 3D-printed. Further analysis on energy absorption should be applied to numerical methods that give reliable results. This will allow many tests to be performed without the destructive nature of tests carried out in laboratory conditions.

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