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Professional paper

Strength Analysis of an Electric Scooter Frame During Simulation of an Obstacle Collision at 45 Degrees

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Abstract: This paper describes the simulation of a 45° angle collision of a modelled electric scooter frame including suspension with a non-deformable wall using the finite element method. Includes creation of a CAD geometric model using the surface method with the necessary components and constraints modelled in Abaqus CAE. During the crash test simulations, the frame was found to pose no danger to the driver in a 45° angle crash simulation at 45 km/h. However, in a 45° angle impact at 85 km/h there is a risk of crushing the rider's leg.

Keywords: CAD system; crash test; mechanical engineering; numerical simulation; single-track vehicle

1 INTRODUCTION

The growing world population and forecasts for the next few decades sustaining its continuous growth [1], contribute to the increase in demand for food, material goods, etc. Increased number of people causes also the growth of cities, and thus the need for efficient transport, which often involves the purchase of one's own means of transport, which is most often a passenger car [2]. Currently, the biggest problem in Polish cities are traffic jams caused by the number of cars, despite the fact that the most frequently used means of transport is public transport, followed by own car, bicycle and on foot. In contrast, the use of scooters as the most common mode of transport is negligible [3]. Between cars and bicycles, scooters are an intermediate means of transport, which can be powered by electricity, thus eliminating exhaust emissions. E-scooters have become increasingly popular in recent years and can help reduce traffic congestion, emissions and parking problems in many European cities [4].

Current trends of car use contribute to high traffic congestion in cities, and increased traffic congestion increases the risk of accidents or crashes [5] along with the involvement of single-track vehicles [6]. To evaluate the safety level of a vehicle, crash tests are conducted, which are commonly used for passenger cars and are destructive tests performed under laboratory conditions. Conducted using real-world objects under study, e.g., a vehicle along with the representation of vehicle occupants by means of crash-test dummies [7]. The course of the test is recorded by cameras and signals from sensors placed on the vehicle and on the dummies. Carrying out crash tests is aimed at improving the design affecting the safety of users and people exposed to the vehicle. The origins of crash testing date back to the 1940s. They were pioneered by Daimler-Benz (now Mercedes-Benz) automotive company development manager Béla Barényi, who worked to improve vehicle passenger safety [8]. Among other things, he developed the concept of a crumple zone, a non-deformable passenger compartment [9] and a safe steering column [10]. Currently, a safety rating is given on the basis of crash tests, and the tests are carried out by independent organizations. In Europe this is Euro-NCAP (European New Car Assessment Programme), while in other parts of the world these works are carried out by other organizations, e.g. in the United States of America these are: NHTSA and IIHS, and in Japan: NASVA. For single-track vehicles, such tests have no clear guidelines and are rarely conducted.

In this article the authors describe a crash test simulation for electric scooters because of their growth on city streets and because they develop a higher speed than bicycles or scooters and can be more dangerous.

Finite Element Method was used to perform the simulation. It is one of the numerical calculation methods used in strength calculations. It is used to solve simple as well as complex engineering problems by numerical methods and is one of many approximate methods that can be used in solving boundary-initial mechanics problems [11]. They are based on systems of partial differential equations [12] (statics and dynamics).

The paper focuses on making and analyzing the strength of the frame of an electric scooter when it hits a non-deformable obstacle at an angle of 45° with a speed of 45 km/h, which is considered an acceptable speed for mopeds in Poland, and with a maximum speed of 85 km/h that the scooter can reach according to the manufacturer's claims.

2 PREPARATION OF THE DISCRETE MODEL FOR DYNAMIC ANALYSIS

Making a model to simulate a single-track vehicle crash test is more complicated than simulating a passenger car crash test. The suspension of the single-track vehicle plays an important role in the forward impact, which should be properly reflected in the model [13]. The response of the frame during a crash is largely determined by the behaviour of the front wheel and suspension (front fork) of the scooter [14].

For the analysis, an existing electric scooter frame was used and modelled in Abaqus CAE software (Fig. 1) to simulate the crash test. The frame is mostly made of tubular profiles with a thickness of 1.5 - 4 mm. The surface method was used by assigning to each plane appropriate values of its wall thickness. Frame profiles are made of S235JR steel.The type of profiles, their cross-sections and the type of material was taken from a real model made by the manufacturer for which numerical models were made.

In order to more accurately represent the actual operating conditions of the frame structure, the front and rear suspensions were modelled by giving the values of stiffness (front: 21.56 N/mm and rear: 33 N/mm), proportional damping coefficient (2.28 Ns/mm and 2.45 Ns/mm), initial deflection (20 and 22 mm) and travel of the respective shock absorbers (120 and 82 mm). These data were made available for the study by the manufacturer.

It was decided to run a simulation for the worst case, i.e., at maximum cargo hold capacity and for a driver within the 95th percentile of males [15]. The assigned elements were reduced to the centre of gravity points and connected to the model (Fig. 1), giving them an appropriate value of mass and moment of inertia.

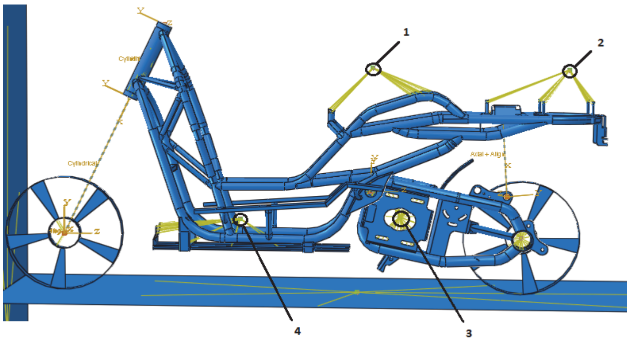

Figure 1 Prepared model for calculation including centres of mass: 1 - driver, 2 - luggage, 3 - engine,4 - battery

Reflecting approximately the real conditions of the event, the non-deformable substrate was also modelled on which the model was placed and the initial load on the scooter with elements attached to it equal to the acceleration of gravity was applied.

The simulation was performed for two cases of collision with the wall at 45° angle at 45 km/h (the standard scooter speed in the city) and 85 km/h (the maximum possible speed).

The prepared model is a simplified one, in which the main simplification is the reduction of significant objects to material points without mapping their external dimensions (Fig. 1).

3 SIMULATION RESULTS

The results of the calculations were presented as the plastic deformation occurring in the frame of the assigned S235JR material from which the frame was made.

The simulation includes strength analysis of the scooter frame including the swingarm, so the obtained strain values in other components of the scooter have not been analysed.

3.1 Simulation Results for a Speed of 45 km/h

The beginning of the simulation carried out is shown in Fig. 2, where the scooter was placed on the substrate and at a 45° angle to the obstacle.

Fig. 3 shows the distribution of deformations after the simulation time of t = 16.5 ms. It was observed that the front rim rotates after hitting the wall it aligns itself parallel to the wall changing the direction of motion. A front rim moving in a different direction than the frame is trying to establish a frame direction consistent with its own. It was found that permanent deformation occurs in the frame only at the places where profiles are attached to the "head" of the frame. They amount to a maximum of 0.03%.

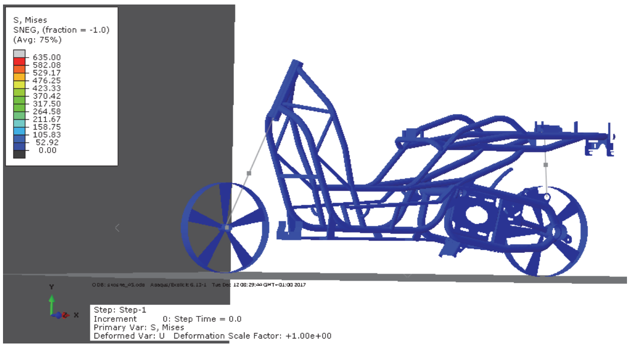

Figure 2 Simulation of a 45° crash at 45 km/h

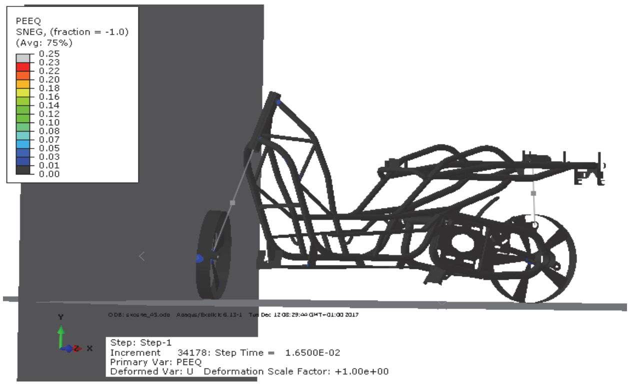

Figure 3 Distribution of permanent deformations occurring in the frame after the simulation time of t = 16.5 ms

In the rest of the simulation, after a time t = 36 ms the frame slowly begins to turn. Fig. 4 shows the distribution of constant plastic deformations in the frame profiles. These can be seen at the bottom of the frame where the battery mounts. The deformation at these locations is approximately 0.1%. An increased deformation at the profile joints in the upper front part of the frame of about 0.11% was also observed. However, these are not yet values that cause plastic deformation of the material.

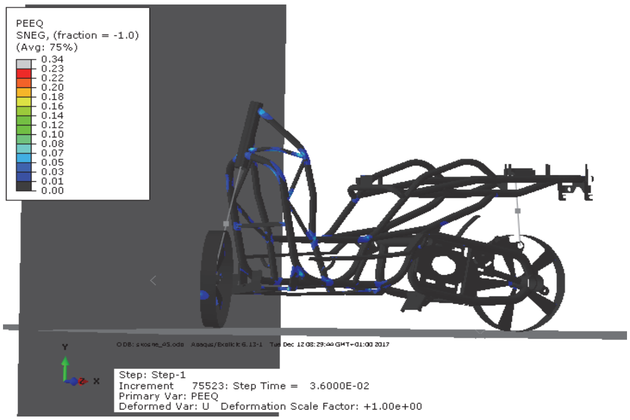

Figure 4 Distribution of permanent deformations occurring in the frame after the simulation time of t = 36 ms

Fig. 5 shows a top view of the frame as it begins to twist. This is accompanied by a slight deformation of the frame where, as previously mentioned, the maximum deformation is about 0.11% and occurs in the front profiles attached to the "head" of the frame and in the lower profiles to which the scooter battery is attached.

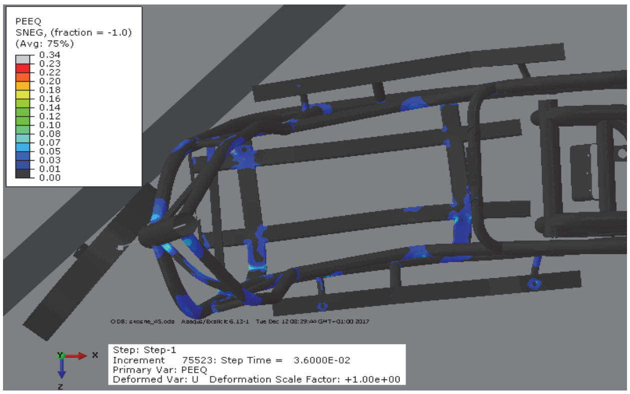

Figure 5 Distribution of permanent deformations occurring in the frame after the simulation time of *t* = 36 ms, top view

When the scooter hits an angled wall (Fig. 6) after the simulation time of *t* = 51 ms the rear rim starts to lift up. The frame of the scooter continues to twist, becoming slightly deformed. The maximum permanent deformation stabilizes at about 0.12% and occurs at the bottom of the frame. On the other hand, in the places where profiles join, they range from 0.03% to 0.1% at the "head" of the frame.

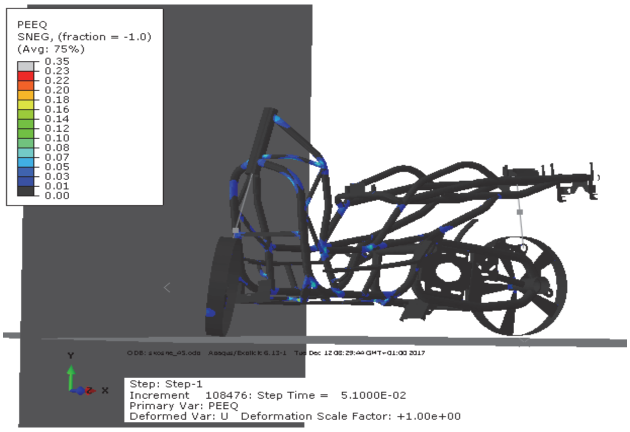

Figure 6 Distribution of permanent deformations in the frame after the simulation time of *t* = 51 ms

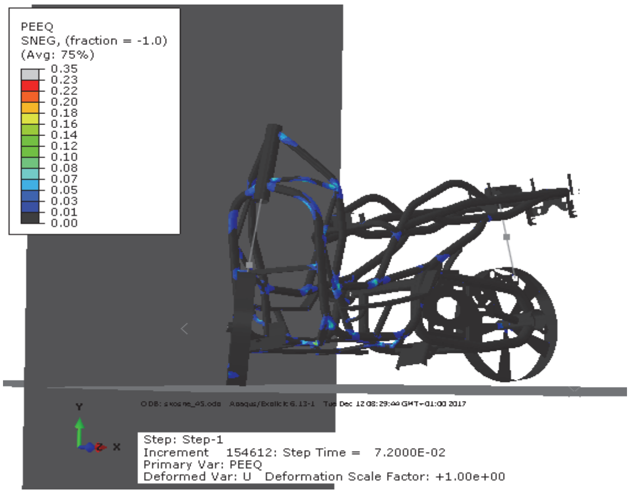

Figure 7 Distribution of permanent deformations in the frame after the simulation time of *t* = 72 ms

The situation presented in Fig. 7 corresponding to the simulation time of *t* = 72 ms does not differ from that shown in Fig. 6 as far as the values and locations of permanent plastic deformations are concerned. The back of the frame along with the rim rises higher and the scooter frame turns. A top view of the frame is illustrated in Fig. 8. It can be seen that the frame has deformed slightly compared to Fig. 5 (with simulation time of *t* = 36 ms).

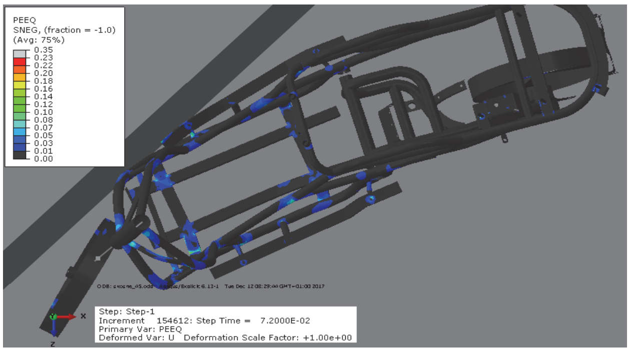

Figure 8 Distribution of permanent deformations occurring in the frame after the simulation time of *t* = 72 ms, top view

In Fig. 9, an increase in strain values was observed in the rear part of the frame reaching a value of about 0.07%, while the maximum strain occurring in the frame is about 0.11% and occurs at the junction of the driver's seat transverse mounting profile with the frame.

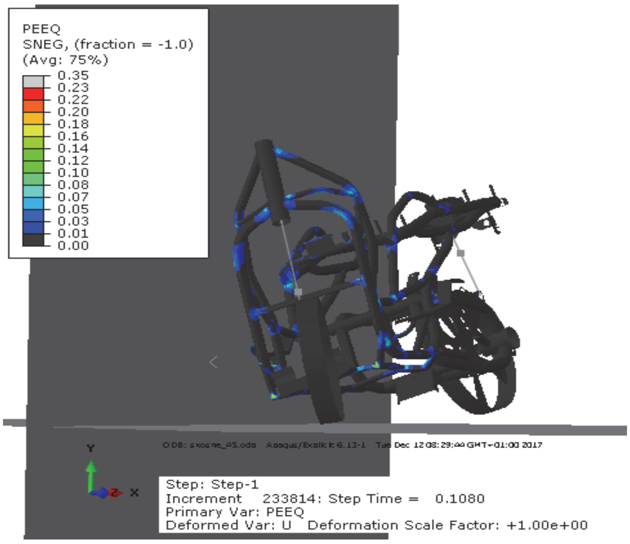

Figure 9 Distribution of permanent deformations occurring in the frame after the simulation time of *t* = 108 ms

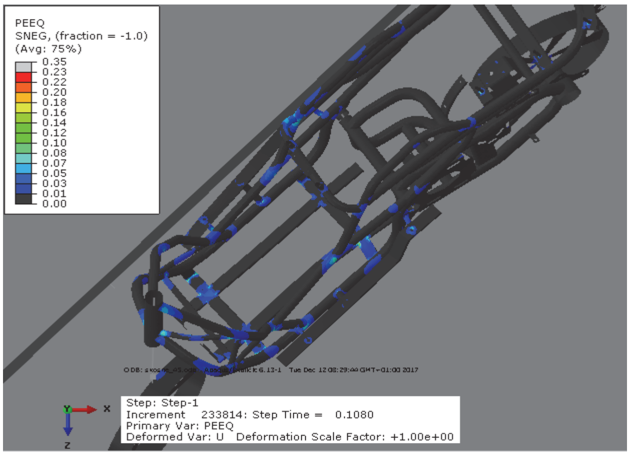

Figure 10 Distribution of permanent deformations occurring in the frame after the simulation time of *t* = 108 ms, top view

Fig. 10 shows the distribution of constant deformations in the frame in top view. It is observed that the front part of the frame starts moving away from the wall and the rear part hits it. The side profiles serving as support for the driver's legs were not deformed after the impact with the wall.

After the simulation time of *t* = 121.5 ms (Fig. 11) the front rim of the scooter was observed to rise. In this situation, the scooter is in the air as the rear rim is also raised. The strain distribution shows that the highest strain values occur in the lower part of the scooter at the bends of the battery mounting profiles and is about 0.14%. Also noticed is an increase in deformation in the rear of the frame near the luggage rack mount.

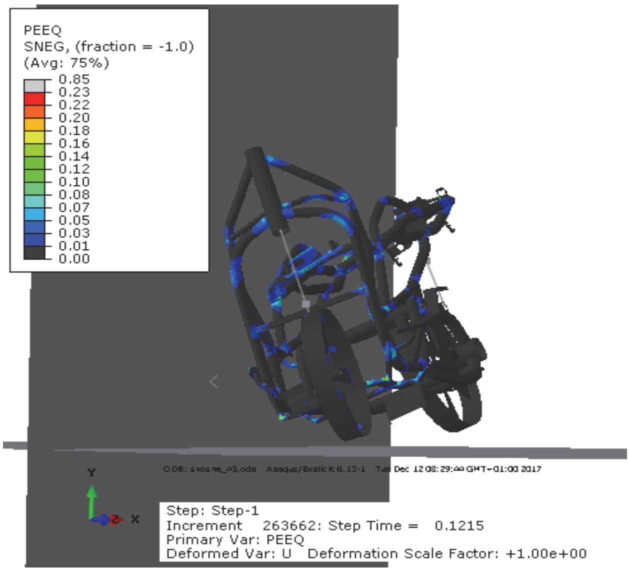

Figure 11 Distribution of constant deformations occurring in the frame after the simulation time of *t* = 121.5 ms

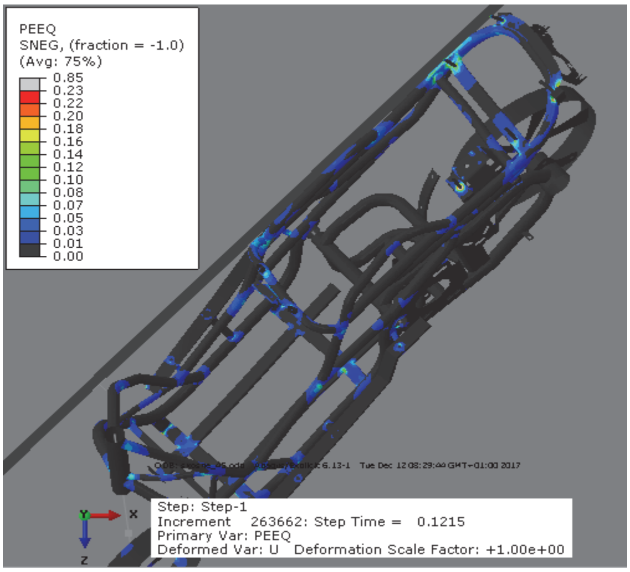

Figure 12 Distribution of deformations occurring in the frame after the simulation time of *t* = 121.5 ms, top view

The largest permanent deformation after the simulation time of *t* = 121.5 ms occurs on the profiles fixing the rack to the frame and amounts to approx. 0.16% (Fig. 12). According to the drawing, the entire rear part of the frame is in contact with the wall, while from the front to the middle part the frame moves away from it.

Fig. 13 and Fig. 14 show the situation after time *t* = 150 ms indicating the end of the simulation.

In Fig. 13 the scooter model is in the air and tilting towards the wall. The plastic deformations occurring in the frame changed slightly compared to the simulation condition shown in Fig. 11 and Fig. 12. It is observed that the transverse profile of the driver's seat mount has deformed and the largest local permanent plastic deformation occurring on it is about 0.2%.

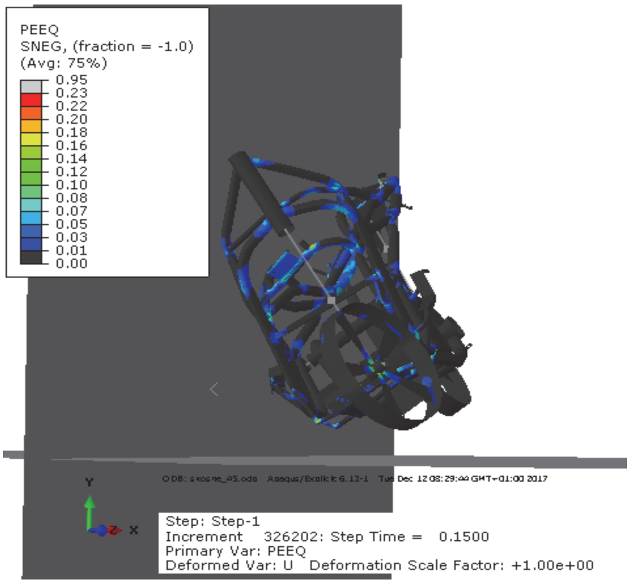

Figure 13 Distribution of permanent deformations occurring in the frame after the simulation time of *t* = 150 ms

The rear part of the frame where the luggage is fixed was deformed significantly, as well as the bottom part (battery fixing profiles) (Fig. 14). However, the rest of the frame has changed its shape slightly. The profiles serving as support for the rider's legs were not deformed. Also, the distance between the front and rear of the scooter frame has not decreased.

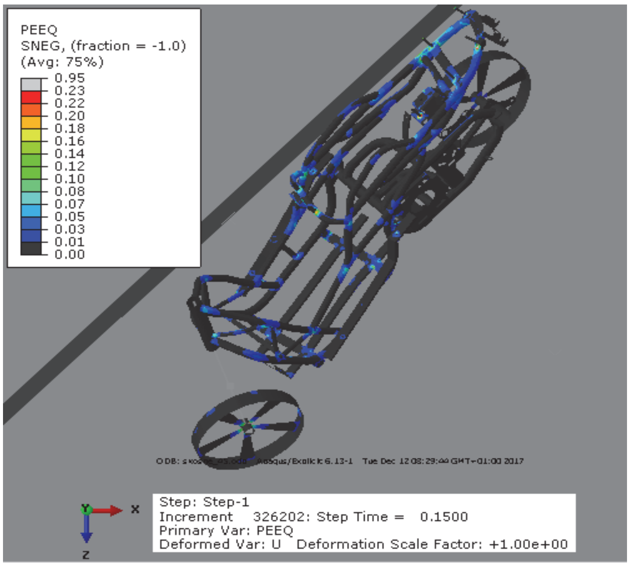

Figure 14 Distribution of permanent deformations in the frame after the time of *t* = 150 ms top view

The kinetic and total energy of the scooter frame was measured during the simulation. On their basis the dependence plot between the ratio of kinetic energy to total energy and simulation time was prepared (Fig. 15). The red points on the graph represent the energy ratio at the moments of time for which the characteristic events during a 45° collision at 45 km/h are shown above.

Analysing the graph it was found that the first-rectilinear-section of the graph corresponds to the rotation of the front rim of the model until it is parallel to the wall. Then the "head" of the frame is deformed. At 30 ms the frame hits the wall causing a rapid drop in kinetic energy. The decrease and then fixation of a constant value of kinetic energy corresponds to the time period during which the entire frame turns. The next stage visible on the graph is a rectilinear section at 100 - 110 ms indicating that the side of the model hits the wall at the height of the rider's seat. It denotes a sharp drop in kinetic energy resulting from a drop in the rider's kinetic energy. The front of the frame moves away from the wall and the front rim starts to lift. Further reduction in the energy value is due to the lack of deformation of the model. The frame rises up and turns sideways toward the wall.

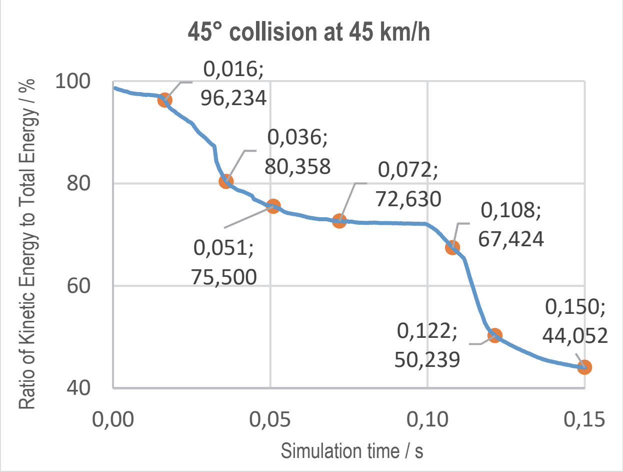

Figure 15 Graph of the relationship between kinetic energy and total energy from the time of impact at an angle of 45° for a speed of 45 km/h

3.2 Simulation Results for a Speed of 85 km/h

Similarly, a collision between an electric scooter and an obstacle set at an angle of 45° at 85 km/h was simulated. The scooter frame behaved almost identically to the lower speed case with higher strain values (due to higher kinetic energy at higher speed). It was noticed that the deformation values were large enough to cause cracks at the frame mounting points at the bottom of the frame (near the battery). However, the calculation model was simplified and the size of the battery that would stiffen this region of the frame was not mapped, so it can be assumed that this area is more robust than in the modelled case and will not cause danger to the vehicle user.It can be assumed that the battery mounted in the actual model (as an additional element of the structure) will have a positive effect on the stiffness of the frame.

The energies occurring during the collision for both velocities were compared (Fig. 16). Analysing the obtained graph, it was found that the smallest decrease in kinetic energy was obtained at the end of the simulation for the impact test at 45°, and its course for both speeds has identical characteristic locations, only at the lower speed it is distributed over a larger time range.

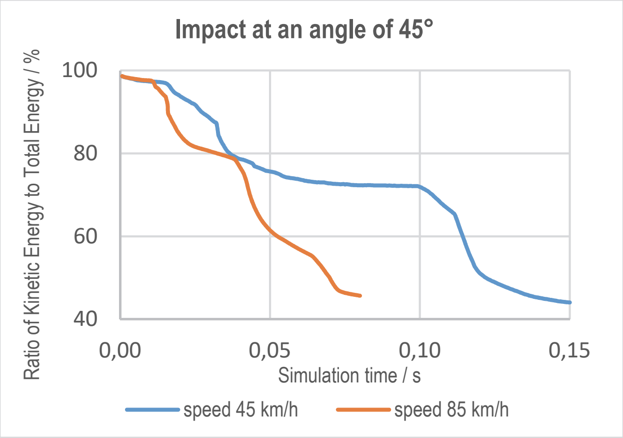

Figure 16 Comparative graph of kinetic energy/total energy ratio versus time for 45° impact at 45 km/h and 85 km/h

4 CONCLUSION

It should be emphasized that the model adopted for calculations is a simplified model. For this reason, the crash test results obtained relate to the worst case, as the external shape of the battery pack or engine should additionally stiffen the frame structure and the rider leaves the rider's seat as a result of the crash. In the case of crash tests, which would be aimed at mapping human behaviour, it would be necessary to model it properly, and since in this study the scooter frame was analysed on the basis of a simplified model, so the rider was simplified to the mass point.

In crash tests of driving into a wall at a 45° angle for both speeds (45 and 85 km/h), the scooter does not "drive" into the wall but turns according to its alignment. For these cases, both simulations are very similar to each other, and the graph (Fig. 16) showing the relationship between the ratio of kinetic energy to total energy and the simulation time is similar in both cases, only at 45 km/h it is more extended in time. The total energy absorbed during the turn, for both speeds, is about 55%.

The condition of the frame during and after the simulation for the 45 km/h case shows that the largest deformation of 0.16% was in the rear part of the frame where the luggage rack is attached. This is not a value that causes the material to break, and plastic deformation in other parts of the frame does not cause a danger to the rider. On this basis, it was concluded that the simulated frame deformation did not endanger the life or health of the rider.

At 85 km/h, on the other hand, it was noticed that the frame profiles in the area of the battery mounting undergo significant deformation that can cause the rider's leg to be squeezed against the wall. On this basis, it was concluded that the vehicle frame could cause injury (crushing) to the rider's leg. However, it should be noted that the battery is mounted in this area, which stiffens the frame considerably, and this was not included in the model.

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