PASSIVE SAFETY OF A BUGGY-TYPE CAR IN THE ASPECT OF A DYNAMIC ANALYSIS OF THE FRAME

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received 4 October 2018, revised 24 April 2019, accepted 30 April 2019

Abstract: This article presents passive safety issues of a buggy-type car. The issue has been presented in the context of the dynamic impact analysis of the aluminium frame of the vehicle into a rigid wall. The study was conducted using the finite element method in the Abaqus® software. With regard to numerical calculations, a dynamic impact simulation was performed, which defined the critical areas of the structure. Numerical analysis allowed to obtain both the state of the strain of the frame structure and the characteristics of the construction work during the impact. The results of the research provide high-quality prepared FEM model.

Key words: Passive Safety, Finite Element Method, Dynamic Impact Analysis, Overload, Abaqus

1. INTRODUCTION

Nowadays, the safety aspect of drivers, passengers and other members of the traffic plays an important role in the automotive industry. Constant striving to minimise the harm resulting from a collision is a major aspect of the need to increase the level of road safety. The most advantageous solution, directly affecting the safety level in the event of potential collisions, is the ability to disperse kinetic energy within the plastic deformation of the structure. The work mainly involved passive safety issues. Passive safety constitutes a very important issue regarding the driving of passenger cars. Generalised division of security into passive and active was made by Bel Barneyi and Hans Scherenberg (Autokult, 2014). The division of passive and active safety in the automotive industry has been widely used since 1966 up to today. Passive safety systems provide all technical solutions to ensure the maximum possible protection for the driver and passengers in the event of a potential collision (Bolton, 1982). The additional task of this type of solution is also to reduce the impact of accidents on people being outside the vehicle. A brand known today as Mercedes-Benz (Bolton, 1982) is the precursor of passive safety in vehicles. The most important elements of the vehicle taking direct part in the process of increasing passive safety are the right bodywork and chassis. The right bodywork design, including lateral reinforcements, controlled crumple zone and ‘safety cage’, has a direct impact on collision safety. In addition, most vehicles have a collapsible steering column that absorbs part of the impact energy, seat belts, airbag systems, head restraints, engine mountings that prevent it from being in contact with people in the vehicle and no curved and sharp elements around the dashboard – increased security. Figure 1 shows exemplary front and lateral reinforcement and controlled crumple zones.

One of the most important elements of a vehicle design that directly affects passive safety is the vehicle frame. The design provides any reinforcements against lateral impacts, safety cage or additional crumple zones (Milanowicz et al., 2018) – the purpose of which is to absorb energy (Estrada et al., 2017).

Fig. 1. Reinforcement of the frame with the crumple zone (Szkielet, 2017)

Fig. 2. An example of a buggy vehicle (Jurczak, 2017)

Many research works introduce the problem of various energy-absorbing solutions, which aims to preserve the highest level of energy absorption because of their properties during crushing (Alavi and Khodabakhsh, 2015). Different energy-absorbing solutions by using specific cross-sectional shapes, the thickness of their walls or the incorporation of specific ‘triggers’ can directly influence the level of energy absorbed because of crush generated during a collision (Ferdynus et al., 2018). The work presents the subject of the numerical analysis of dynamic impact of the

DOI 10.2478/ama-2019-0010

buggy-type vehicle frame in the scope of passive safety (Guangjun et al., 2017). Owing to the specifics of the design of this type of vehicle, the frame is the main construction element that has main impact (Sun et al., 2018) on the safety level in the event of an impact (Gui et al., 2018). Buggy cars were designed and served initially to drive through dunes on the beaches and deserts. Over time, they were also adapted for recreational and off-road riding. Their characteristic feature is the open body, sturdy suspension and exposed engine located in the rear of the vehicle. Figure 2 shows the graphical representation of a typical buggy vehicle.

2. SUBJECT OF THE STUDY

The subject of the study was the construction of welded buggy frame. The geometric model was designed in Inventor CAD software and then imported to Abaqus 6.14 CAE software (Rozylo, 2016). The material model of the aluminium alloy 6061 used for the designed frame was based on the use of plastic–elastic features with bilinear characteristics, which were obtained from the Inventor materials' database. Details of the material data for aluminium alloy are given in Table 1.

Tab. 1. Material properties for aluminium alloy 6061

	Unit	Numerical value
Young's module	MPa	70,000
Poisson's ratio	-	0.33
Yield point	MPa	175
Tensile strength	MPa	250
Elongation at break	%	8
Density	kg/m³	2,700

The geometry of the frame includes thin-walled profiles with circular and square cross sections with a 3-mm wall thickness as well as thin-walled square cross-sectional profiles (Deng et al., 2018) with a wall thickness of 1.5 mm included in the front crumple zone. Figure 3 shows the graphical representation of the frame model.

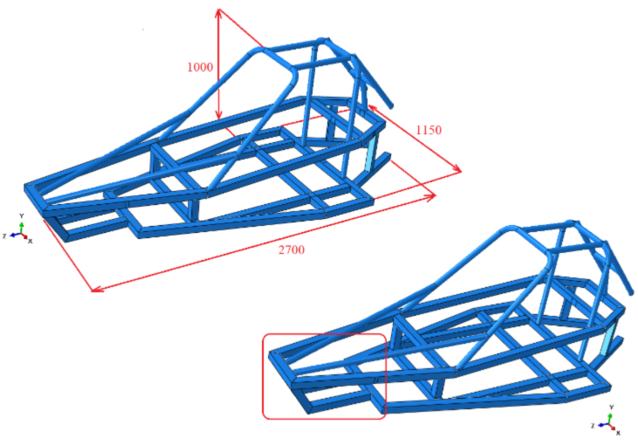

Fig. 3. Geometrical parameters of the model and crumple zone

With reference to the frame structure, Fig. 4 shows the area of the structure with base thickness and the crumple zone with reduced thickness.

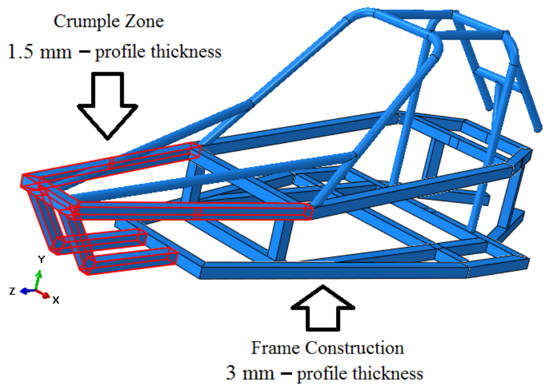

Fig. 4. Frame construction detailing areas

It was assumed that the designed frame was welded, thus importing the frame model from Inventor to Abaqus enabled the import of the entire structure as a single geometric model.

3. RESEARCH METHODOLOGY

Numerical analysis was based on the finite element method carried out as a dynamic issue (Ferdynus et al., 2018). The study investigated the way in which the energy was absorbed by the structure, with particular emphasis on the behaviour of the crumple zone. Additional attempts were made to identify the most sensitive areas that could adversely affect the driver's safety. The study investigated reaction forces, velocities, displacements, overloads and stresses in the dynamic impact to a rigid non-deformable wall (Lonkwic et al. 2015). Within the numerical analysis, a material model was defined based on the properties presented in Table 1. The impact process was defined based on the known parameters: the initial frame velocity of 50 km/h (about 14 m/s) and the potential duration of the impact process of 0.045 s. The distance travelled by the frame during the impact was calculated using equation (1):

$$s = v * t \tag{1}$$

where s is the distance, v is the velocity and t is the time.

The potential distance that was designated as part of the impact process was approximately 625 mm. The obtained value represents about 23% of the global frame length. This value, however, is not a parameter indicating the true depth of the structure into the rigid wall due to impact simulation – because of the inherent structural rigidity, material density and thickness, additional loads simulating engine load and driver mass. An important factor directly influencing the reduction of frame structure's length because of impact is the energy absorption and buckling mode (occurrence of local or global buckling) of the structure. Boundary conditions were set out as part of this work, which were connected with the complete restraint of a rigid plate (wall) and defining the frame structure's initial velocity of movement towards the plate. The frame structure additionally had determined concentrated masses, bound with a coupling type tie with proper frame surfaces, in order to simulate the load resulting from the engine's and person's own mass (round tags) – as shown in Fig. 5. In addition, a measuring point (triangular tag) was generated so as to collect the results for velocity and movement of the system.

DOI 10.2478/ama-2019-0010 acta mechanica et automatica, vol.13 no.2 (2019)

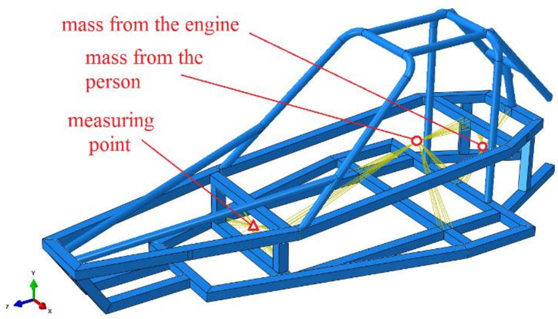

Fig. 5. The frame structure with the included loads from the engine and the person together with the presented measuring point

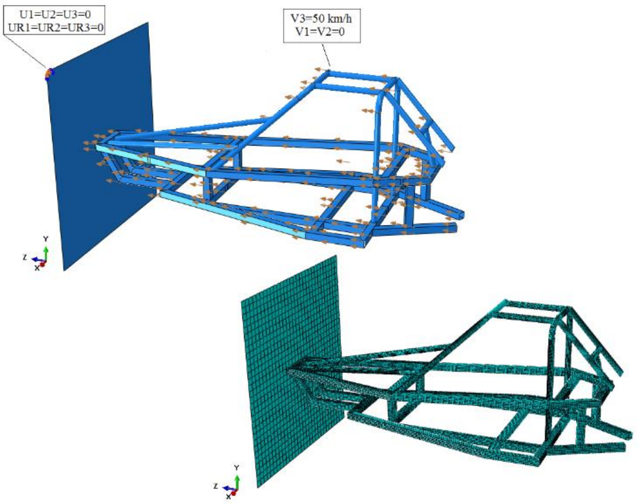

Fig. 6. Boundary conditions and discrete model

The boundary conditions referring to the complete restraint of the plate simulating a rigid wall were set out through the blocked possibility of movement and rotation of the plate in any direction. In the edge of the plate, a reference point was set out, closely connected to the entire geometry of the shell element in which all degrees of freedom were successively locked. In the case of the frame structure, a boundary condition was implemented to define the initial velocity parameter aimed towards the non-deformable plate. This way, the boundary conditions were described, which made possible the further simulation of the dynamic impact process with the inclusion of the possibility of reflection of the frame from the plate, as an effect of the structure's inertia. The discretisation process of the numerical model was conducted based on the use of shell-type elements (Wysmulski and Debski, 2017). The numerical model was described using a type S8R finite element mesh with the square shape function, constituting finite elements with 6 degrees of freedom in each of the 8 nodes for one element (Rusiński, 2000). The total number of finite elements describing the model is 140,000, whereas for the nodes, it is 91,500. The plate was modelled as a non-deformable object and the frame structure as deformable (Zienkiewicz, 2000). Figure 6 shows the boundary conditions and discrete model.

4. RESULTS

The testing results presented in the scope of passive safety were derived based on the conducted numerical analysis. As a part of the FEM analysis (Rozylo et al., 2018), a reaction value was initially evaluated, which was generated in the rigid plate hit by the frame structure. Figure 7 shows the characteristics of reaction force versus time.

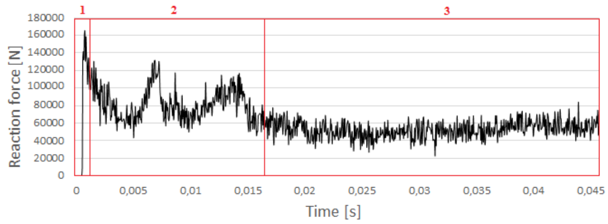

Fig. 7. The characteristic of the reaction force versus time

As a part of the obtained characteristic of the reaction force, in relation to the time of the analysis duration, it was observed that the work of the structure is divided into a number of stages. Contact interactions (in tangential and normal directions, with a friction coefficient of 0.15) were defined between the column ends and the rigid plate supports in tangential and normal directions (Ferdynus, 2013). Applied contact relations allow correct simulation of the crash test. Changing the friction coefficient has a negligible effect on the work of construction. Initially observed was the stage in which the maximum reaction value occurred as a part of the contact of the striking object with the rigid plate. The maximum reaction value is 165,180 N. The second stage is connected with the influence of the crumple zone. Specific reaction spikes occurred as a part of the second stage because of the 'folding' of the front crumple zone. The third stage is connected with the stabilisation of the reaction level (force range: 4,000–6,000 N). Fig. 8 shows the dynamic impact process.

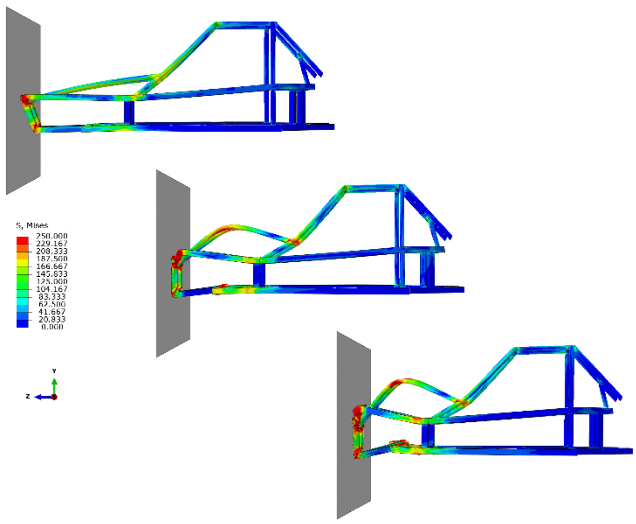

Fig. 8. The frame damage in 0.0045 s, 0.0225 s and 0.045 s

The test results point to the occurrence of a high level of structure deformation in the area of the crumple zone. Regarding the dynamic (explicit) analysis, strain-rate sensitivity (SRS) parameter is very important. SRS is a parameter that characterised deformation mechanism of materials. The definition of this parameter is mainly based on incremental changes in strain rate during dynamic tests (performed at fixed temperature and microstructure to determine adequate changes in flow stress), which are commonly called as strain hardening. Strain hardening is the strengthening

DOI 10.2478/ama-2019-0010

of a metal or polymer by plastic deformation. Incremental tests for SRS minimise the effects of changes in structure, temperature and strain hardening during testing and are used to determine the relationship between dislocation velocity and stress at constant structure. In case of metals, the Johnson-Cook model of material is often used. The Johnson-Cook model even includes strain-rate sensitive failure criteria that allow to obtain advanced numerical results in dynamic analysis.

In addition, the velocity in the measuring point, previously shown in Figure 5, was presented as a part of the testing results. Figure 9 shows the characteristic of the velocity and displacement in the time of the analysis duration.

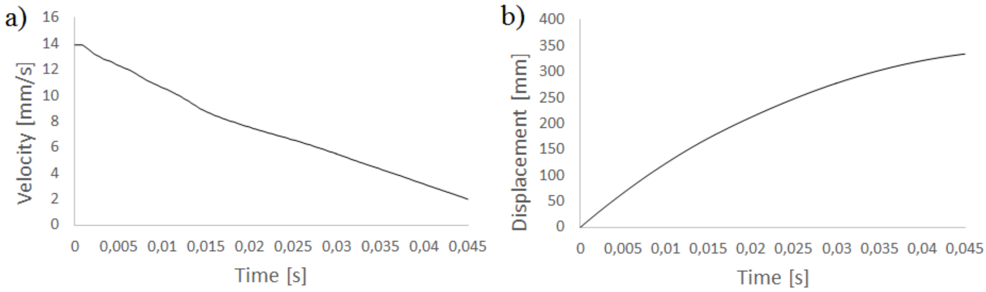

Fig. 9. Operation characteristics: (a) velocity and (b) displacement

It was observed that the velocity was reduced in an almost linear manner to the end of the time of the analysis duration, where, from the initial value of 14 m/s, it has achieved 2 m/s within 0.045 s. For the structure to brake completely, it was necessary to increase the numerical analysis time; however, it would entail a significant increase in the numerical calculation duration time. The movement of the frame structure (shortening of the crumple zone), which was observed in the measuring point, reached the value of 335 mm, which constitutes barely 12.5% of the entire structure length. The area of the shortening relates mainly to the area of the crumple zone, which has no negative effect on endangering the safety of the person driving the vehicle. The parameter that points directly to the possible occurrence of the negative effect on health and even life of the person is the overload. The parameter is known as a state of the body subjected to external forces and the resultant of which creates an acceleration different from that resulting from the gravitational force *g*. The overload is a multiple of the standard acceleration of gravity. The overload level of *5g* can be a deadly value for the human in many cases, however, only in the case of a few seconds of lasting of the effect. Nevertheless, in the case where a very high level of overload occurs, it is desirable that time of this effect is as short as possible. The overload characteristic versus time is presented in Fig. 10.

Because of the obtained overload result, it is possible to directly state that the obtained overload range, beginning with the initial moment up to 0.045 s, does not constitute a direct threat to human life. The overload factor should be as low as possible, because of its negative effect on the human body during a long period of overload. Only the initial stage in which the overload level reaches *60g* may negatively affect a human, which, however, is the value from the area of moderate injuries. In the first stage of impact, the value of the overload factor is high, whereas in the second half of the analysis, the value decreases three times. The remaining range of overloads until the end of the time of the analysis duration shows the work of the test system within the range allowed for maintaining the permissible safe level. The analysis of the designed frame shows that the thickness of the frame structure should be reduced (from the pre-assumed thickness of 1.5 mm of crumple zone and 3 mm of rest of the frame, as shown in Fig. 4), in order to reduce the level of overload. Constructions should usually be designed so that the initial overload 'peak' was the smallest as possible and the remaining range of the overload characteristics does not exceed a few *g*, as human-safety values.

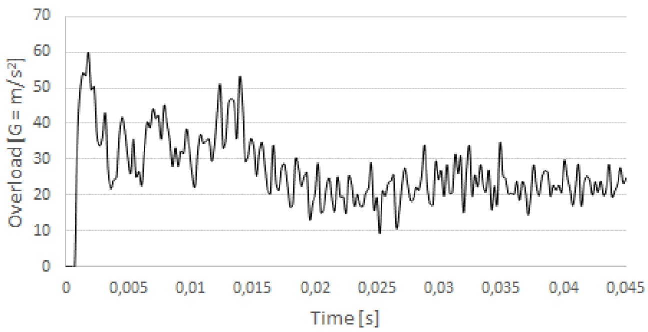

Fig. 10. The overload characteristic versus time

5. CONCLUSION

On the basis of the conducted simulation tests, a new contribution to the development of the described subject is presented, which is the analysis of not only the crumple zone but also the complete frame of the vehicle. A lot of scientific publications present only crumple zones or energy-absorbing elements. The author's contribution includes the analysis of the structure, using the example of a vehicle frame, taking into account both the crumple zone and the rest of the structure.

The aim of this work was the dynamic analysis of the buggy-type vehicle rack frame for the purpose of crash testing. After analysing the gathered results, conclusions regarding the safety of this type of construction were drawn. On the basis of the developed reaction, time characteristic, a multi-stage structure work was observed, beginning with the initial capture of the maximum value, through the work of the controlled crumple zone, ending with the stabilisation of the reaction. In the impact process, it was observed that the main work of the frame, with regard to the energy absorption, is performed by the front crumple zone. The designated velocity and movement values in the measuring point were located right behind the crumple zone point to the correctness of the structure work. The shortening of the structure that equalled

335 mm in the crumple zone does not constitute an immediate danger to human safety. The level of the overload equalling *60g* in the initial moment and from 0.015 to 0.045 s, where the overload range is about *20–30g*, does not constitute danger to human life, because of the occurrence of the dominating part of the range in the permissible area.

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