Side Impact Analysis of the Bus Frame Structure

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Abstract. Vehicle bodies and structures should be designed to absorb and redistribute as much impact energy as possible, thus protecting the driver and passengers from injury. The deformation zone of the vehicle in the case of a side impact is smaller than in the case of a front impact. A side impact collision directly affects the structure of the vehicle. Composite materials may be used in the structure to reduce vehicle weight and improve vehicle deformation. Bodies and structures where composite materials are used have a higher SEA value. Using Ansys software package according to UN / ECE Regulation No. 95, a side impact simulation, when a deformable barrier moving at a speed of 50 km/h impact to a structure was performed. The simulation was performed with a steel and hybrid bus frame structure. The simulation results show that the deformation of the hybrid frame structure is close to the deformation of the steel frame structure and the SEA value is 12% higher.

Keywords: Bus frame · Side impact · Kinetic energy · SEA

1 Introduction

Side impact accidents are one of the most dangerous accidents that happen every day. Although according to Liang and Le [1] the most dangerous accident for buses is a rollover. According to the sources that provide accident statistics by type of accident side impact accidents account for about 20% of all accidents. The incidents of corner, front and rear collisions respectively are as follows: 30%; 4%; 46% [2]. In 2018 9,670,000 traffic accidents related to vehicle collisions were recorded in the United States. The number of side-on-road accidents recorded in Europe is around 35–40% of all vehicle-related accidents [3].

The consequences of side impact accidents are painful not infrequently resulting in passenger deaths. The deformation zone of the vehicle in the case of a side impact is smaller than in the case of a front impact. The impact of a side impact is directly affected by the structure of the vehicle, which affects the safety of the occupants. Unlike in the case of a frontal or rear impact in the case of a side impact the impact energy is transmitted directly to the vehicle structure which directly affects the occupants. The structure of the vehicle should be constructed that in the event of a side impact accident, the structure absorbs the energy of the side impact and protects the occupants from injury

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in the event of an accident. Side beams and reinforcement elements should withstand side impact force, absorb energy and protect occupants [4, 5].

The risk of side impact is distinguished by the fact that it is not possible to fit sufficient deformation zones in the lateral parts of vehicle structures as in the front and rear parts of vehicles. This limitation is even more pronounced in frame structures where square or rectangular profiles are used instead of shaped steel sheets. In order to minimize the consequences of a side impact vehicles shall be designed in a variety of ways to efficiently absorb the energy generated by the side impact so that it passes as little as possible to the occupants inside the vehicle.

Composite materials can be used in structures to increase the amount of impact energy absorbed. However, replacing steel with a fiberglass composite can lead to unacceptable deformations of the bus frame structure that may not ensure the safety of the driver or passengers in the event of a traffic accident leading to safety tests modeling various impact scenarios [6].

2 Methodology

Safety tests shall be performed to assess the strength and safety of the vehicle and the load on the driver and passengers. Side impact tests may be carried out in accordance with various requirements, directives, rules or standards:

- Federal Motor Vehicle Safety Standard (FMVSS 214). The barrier strikes a stationary vehicle at a speed of 54 km/h. In this test, the barrier is inclined by 27 degrees, so that the speed of the barrier splits into two components: a speed of 48 km/h in the direction of the Y axis and a speed of 25 km/h in the direction of the X axis. The width of the barrier is 1,676 mm and the ground clearance is 279 mm. The ground clearance of the deformable element is 330 mm. The weight of the barrier is 1,368 kg. The dummies are used in the front and rear seats;
- side impact test according to (UN / ECE) Regulation No. 95. A movable deformable barrier (MDB) strikes the test vehicle at a speed of 50 km/h. The barrier and the vehicle are arranged so that an angle of 90 degrees is formed between them. The barrier mass is 950 kg and a width of 1,500 mm. The ground clearance of the deformable element is 300 mm. The dummies are used only in the driver's seat [7].
- Euro-NCAP side impact test. This side impact test is very similar to (UN/ECE) Regulation No. 95 test. The difference is that according to the Euro-NCAP side impact test dummies are used in both the front and rear seats [8].

Such safety tests are quite expensive, so many manufacturers use numerical simulations based on the finite element method (FEM), which evaluated the strength and safety of the structure at the design stage to reduce these costs [9–11]. The results of the dynamic analysis make it possible to compare different structures and identify their weaknesses, which can deform under critical loads beyond the limit values. When a model is a tubular spatial system consisting of individual elements connected into one common node it is practically impossible to solve it by conventional methods, so in this case FEM are used [12].

In vehicle collision modeling using FEM the vehicle is divided into FE the contacts of the individual elements are described and the initial data (weight, energy absorption coefficient, body deformation depth, etc.) are entered [13].

The amount of energy absorbed by vehicles depends directly on the materials used in the structure of the vehicle, their density, yield strength, the wall thickness of the components, the geometry and the deformation zones.

When comparing the deformations of composite materials, they differ from metallic materials.

In metallic materials energy is dissipated through plastic folding, material hardening, and through heat loss. Composite materials in contrast dissipate energy due to external and internal friction and fiber bending and kinematic dispersion as the material decomposes. These properties give composite materials advantages in improving impact resistance. When assessing Specific Energy Absorption (SEA) it may be higher. Using composite materials, the same impact resistance of a structure can be achieved as with metallic materials but using composite materials the structure is lighter [14].

SEA also called absorbed energy per unit weight is a very important measure to reduce the weight of a structure and is used to assess the energy absorption capacity of structures [15, 16]. The absorption of specific energy can be calculated according to the equation [14]:

$$SEA = \frac{W}{\rho \cdot A \cdot \delta} = \frac{\int_0^\delta F \cdot d\delta}{\rho \cdot A \cdot \delta}. \tag{1}$$

where W – the total energy absorbed J; ρ – density, kg/m^3; A – cross-sectional area, m^2; δ – total compressive deflection mm; F – the compressive force, N.

According to the definition of impact suitability it is understood that the ideal, impact-friendly material used in vehicle structures must perform two main actions in the event of an accident: first, to absorb the kinetic energy of the impact; second, to dissipate this kinetic impact energy over time to ensure that the deceleration of the vehicle is less than the critical value above which passengers would suffer irreversible injury. According to Jacob [17] comparing two different materials with similar energy absorption properties a material with a higher specific energy absorption value and which has dissipated this energy over a longer period of time would be considered more impact resistant.

3 Side Impact Simulation and Results

The modeling of the side impact on the bus frame structure shall be performed in accordance with Regulation of the United Nations Economic Commission for Europe (UN/ECE) No 95. According to this Regulation a 950 kg barrier moving at a speed of 50 km/h strikes the structure of a bus frame [7]. The modeling process and accepted boundary conditions are presented below.

The geometric model of the bus frame structure and barrier was prepared by the Rhinoceros (Rhino version 6) program. In the next step, the model was uploaded to the

Ansys Workbench program. In side impact modeling were use mixed shell and solid FE. In the steel frame structure, all elements are connected using the bonded type and, in the hybrid, the bonded type and the cohesive zone model (CZM). Frictional was used to describe the contact of the frame structure with the base. The values of the coefficient of friction of a car tire with a dry road surface range from 0.8 to 0.9 [18]. A coefficient of friction of 0.8 was chosen for the model.

The properties of the materials used in the structure of the bus frame structure are given in Table 1.

After preparing the model it was broken down into FE. The FE frame structure of the bus frame structure consists of 425,495 elements and 430,682 nodes. The barrier in the model is accepted as a deformable body.

Table 1. Mechanical properties of pultruded glass fiber (GFRP) composite material and steel 1.4003 (Stala 400F).

Property	GFRP		Steel 1.4003 (Stala 400F)
	Directionality		
	longitudinal	crosswise	–
Density (kg/m^3)	2,000		7,700
Tensile ultimate strength (MPa)	400		450
Compressive ultimate strength (MPa)	400		–
Young's modulus (MPa)	39,000	4,875	220 · 103
Poisson's ratio	0.035	0.335	0.3
Shear modulus (MPa)	3,358	3,342	–
Yield strength (MPa)	–	–	400

To solve the problem of modeling the side impact to the frame structure the Ansys Workbench program supplement "Explicit dynamic" is used. Using the Velocity command, a speed of 50 km/h is entered into the program. It is at this speed that the deformable barrier (in the direction of the Y axis) collides with the frame structure. Barrier displacement was also limited in the direction of the Z axis. For all bodies the acceleration of free fall in the direction of the Z axis was added.

In the Ansys Workbench program selected for modeling, calculations are performed using the Newmark method. The equilibrium equation for this method is written as follows:

$$[M]\ddot{U} + [C]\dot{U} + [K]U = N, \tag{2}$$

$$\dot{U}_{i+1} = \dot{U}_i + \left[(1-\delta)\dot{U}_i\right] + \left[(1-\delta)\dot{U}_i + \delta\ddot{U}_{i+1}\right]\Delta t, \tag{3}$$

$$U_{i+1} = U_i + \dot{U}_i\Delta t + \left[\left(\frac{1}{2}-\alpha\right)\ddot{U}_{i+\alpha}\cdot\ddot{U}_{i+1}\right]\Delta t^2, \tag{4}$$

$$M\ddot{U}_{i+1} + C\dot{U}_{i+1} + KU_{i+1} = N_{i+1}. \tag{5}$$

where $\ddot{U}$ – acceleration; $\dot{U}$ – speed; U – displacement; $[M]$ – mass matrix; $[C]$ – damping matrix; $[K]$ – stiffness matrix; N – force; t – time; δ – change; α – number of individual elements.

Two bus frame structures were evaluated in the side impact modeling. Because the impact on the bus frame structure, which does not include exterior and interior elements, is modeled, only the mass of the bus frame structure is used, not the total mass of the vehicle. The first structure was made of steel and weighed 966 kg. The second bus frame structure was hybrid and weighed 814 kg. And it is a 15% lighter structure compared to a structure that is made only of steel.

In the developed model the deformable barrier moving at a speed of 50 km/h collides with the bus frame structure which deforms from the impact energy. The frame structure is built on an absolutely rigid surface and as written above contact with a coefficient of friction of 0.8 is described. Contacts are made where the front and rear axles of the bus are located. In solving the problem, it is assumed that the shock-absorbing properties of the surface on which the frame structure moves are not evaluated. The program also sets the numerical simulation of the collision to last 0.75 s. This impact time is sufficient to observe the deformations of the frame structure and to understand the impact resistance properties, as after 0.75 s there is no contact between the barrier and the structure.

The initial position of the structure and barrier is shown in Fig. 1. The following are the results of the numerical modeling of the side impact of the two bus frame structure.

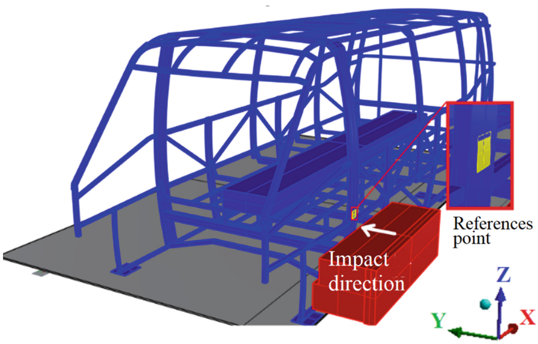

Fig. 1. Initial position of the side impact simulation.

The side impact modeling assumes that the steel frame structure meets safety requirements. It is treated as a reference and the differences in the obtained values are evaluated, which are recorded by side impact modeling with a hybrid frame structure.

Figure 2 and Fig. 3 show how steel and hybrid frame structures deform at different time points (four stages are distinguished).

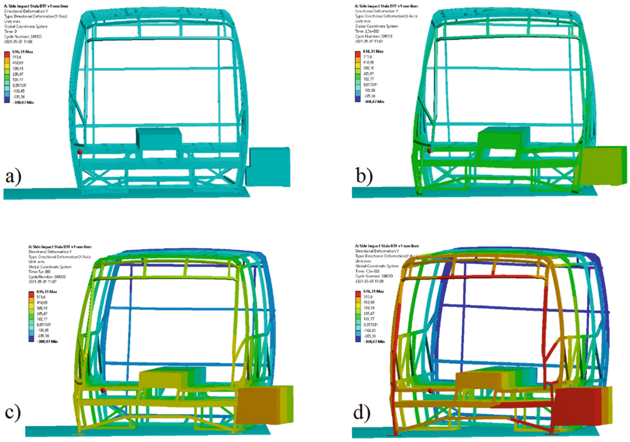

Fig. 2. Deformation progress in steel frame structure: a) start of contact; b) 25 ms from start of contact; c) 50 ms from start of contact; d) 75 ms from start of contact.

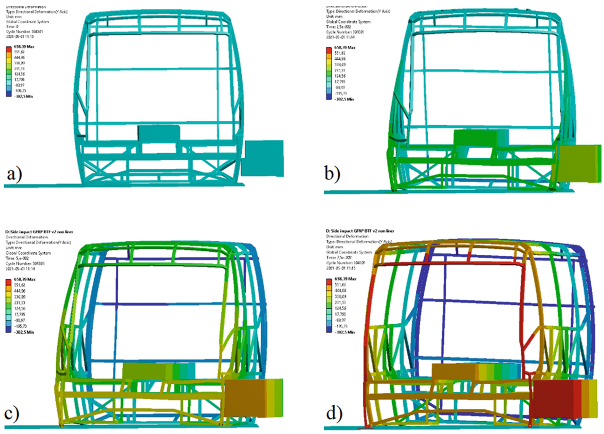

Fig. 3. Deformation progress in hybrid frame structure: a) start of contact; b) 25 ms from start of contact; c) 50 ms from start of contact; d) 75 ms from start of contact.

According to the presented figures of side impact simulations it is noticeable that both the steel and hybrid bus frame structure deforms in a very similar way. At the same moments of time the values of deformations are very close, the deformation zones are identical. The good strength of the hybrid frame structure is also confirmed by the fact that the maximum difference in displacements of the structures reaches 1% (in the direction of the Y axis) and the maximum concentrations of stress are formed in the same places. Also, these two different structures absorb the kinetic energy of the barrier in a very similar way. Figure 4 shows the change in the barrier's total kinetic energy over time. The initial total kinetic energy of the barrier is 91.64 kJ. This value corresponds to an initial speed of 50 km/h (13.89 m/s) for the moving barrier calculated as follows:

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \tag{6}$$

where E_k – kinetic energy, J; m – mass of the structure, kg; v – initial barrier movement speed, m/s.

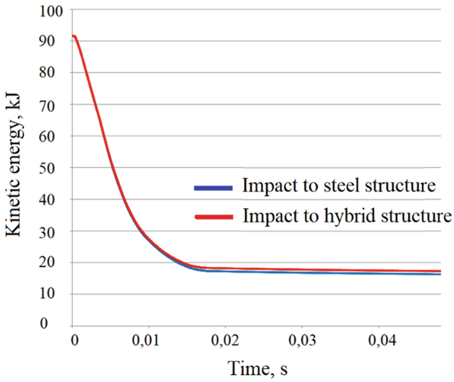

Fig. 4. Alteration of kinetic energy of barrier over time, J.

As shown in Fig. 4 the contact between the moving barrier and the bus frame structure occurs 0.015 s after the start of the test. Upon contact the kinetic energy of the barrier decreases to 18.8 kJ in the case of a steel frame structure and to 19.6 kJ in the case of a hybrid frame structure. As the test continues, the kinetic energy of the barrier remains the same until the end of the test, so the graph provides information for up to 0.04 s. The difference between the kinetic energy of the barrier after contact with the steel and hybrid frame structure is 4%. This difference in kinetic energies is due to a decrease in the mass of the hybrid frame structure. Due to the reduced mass the hybrid frame structure is less inert and therefore less dampens the speed of movement of the barrier and thus the kinetic energy.

Figure 5 shows a comparison of the total absorbed kinetic energy of a steel and hybrid frame structure when a deformable barrier with a speed of 50 km/h impact the structures. According to the presented graph, the value of absorbed energy at all time points in both structures is very close. The graph also shows that energy absorption does not follow a linear relationship, energy absorption is unstable.

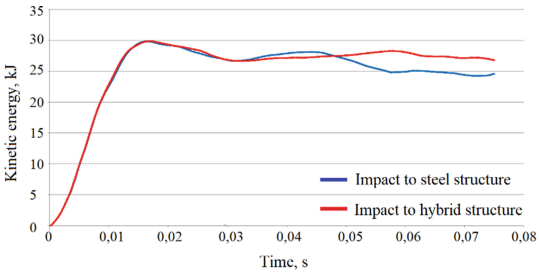

Fig. 5. Alteration of kinetic energy of frame over time, J.

The ratio of absorbed kinetic energy is similar in both steel and hybrid frame structure models. Therefore, it can be said that the hybrid frame structure absorbs impact energy almost in the same way as steel.

Figure 6 shows the change in geometry of different structures after side impact modeling.

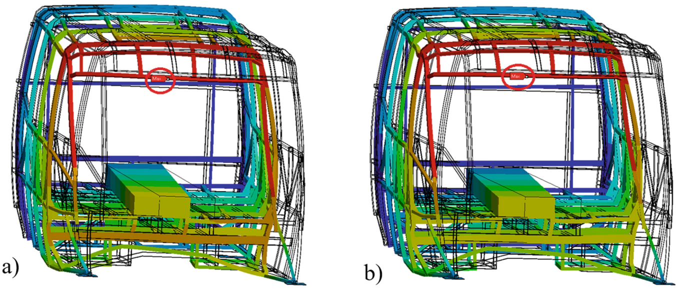

Fig. 6. The contour of the frame prior and after the side impact (black colour - frame contour before side impact): a) steel frame structure (front view); b) hybrid frame structure (front view).

In the steel frame structure, the maximum deformation is received at the top and amounts to 360 mm. Comparing the deformed steel frame structure with the undeformed (Fig. 6a), where the contour of the structure before deformation (black solid line) is shown after a side impact that was in a relatively low position, the maximum deformation is fixed in the upper part of the structure. This result was to be expected, as there are additional structural elements in the lower part of the structure over the entire floor area, which reinforce this part of the structure. The upper part of the structure shall have no additional reinforcements and the structural arches shall ensure sufficient strength of the structure. When evaluating a hybrid frame structure (Fig. 6b), the maximum deformation is also fixed in the upper part of the structure and reaches 387 mm. The difference between these deformations is about 7%. The greater deformation is reached in the hybrid frame structure due to the fact that it was in the upper part that the steel was replaced by a fiberglass composite, the mechanical properties of which are inferior to those of steel.

After performing a numerical simulation of the collision and determining the energy and deformation absorbed by the structures, the SEA can also be assessed. The SEA will be assessed according to Eq. (1). All the quantities required to calculate the specific energy absorption are known. The value of the deformation of the bus frame structure is used to calculate the SEA value, which is obtained by comparing the undeformed and deformed frame structure. In the case of a steel frame structure, they are: $W = 29.85 \cdot 10^3$ J; $\rho = 7,700\text{kg/m}^3$; $A = 0.125\text{m}^2$; $\delta = 0.360\text{m}$. In the case of a hybrid frame structure, they are: $W = 29.89 \cdot 10^3$ J; $\rho = 6,560\text{kg/m}^3$; $A = 0.125\text{m}^2$; $\delta = 0.387\text{m}$.

Calculating the SEA from the values given gives the following values: SEA_Steel = 86.15 J/kg; SEA_hybrid = 97.19 J/kg. The higher value of specific energy absorption is reached in the hybrid frame structure. The difference between the specific energy absorption values in different structures is about 12%. This difference is obtained because the amount of energy absorbed by the hybrid frame structure and the amount of deformation are close to the values of the steel frame structure but in the case of a hybrid frame structure the total structure density decreases significantly (about 15%). The higher the value of SEA, the better the structure is able to absorb energy. The resulting higher SEA value indicates that the use of composite materials significantly reduces the mass of the structure and at the same time maintains the impact resistance of the structure.

4 Conclusion

1. In the structure of a bus frame replacing steel with a fiberglass composite reduces the weight of the frame structure by about 15%. The reduction in mass would have a positive effect on the reduction of exhaust emissions.
2. Modeling of the side impact showed that the deformation of the hybrid frame structure is 7% higher compared to the steel frame structure.
3. Assessing the change of the kinetic energy of the barrier over time and its general change, it can be seen that the kinetic energy of the barrier decreases by about 80% after contact in 0.015 s. The change in the kinetic energy of the barrier in the different structures is very similar and the difference between them is 1.2 kJ. This shows that both structures absorb the kinetic energy of the barrier relatively equally.
4. Assessing how the kinetic energies of frame structures change, it can be seen that they also change uniformly. The difference in kinetic energy between different structures is about 5%.
5. After calculating and comparing the SEA values of different structures, it was found that a higher SEA value is obtained in the hybrid frame structure. This difference is 12%. The obtained result shows that the use of composite materials can ensure high impact resistance of the structure at a lower mass.

References

1. Liang, C.C., Le, G.N.: Analysis of bus rollover protection under legislated standards using LS-DYNA software simulation techniques. Int. J. Automotive Technol. **11**(4), 495–506 (2010)
2. Injury Facts, Type of Crash (2018). https://injuryfacts.nsc.org/motor-vehicle/overview/type-of-crash/
3. Breen, B.: Road safety study for the interim evaluation of Policy Orientations on Road Safety 2011–2020. (2015). https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/study_final_report_february_2015_final.pdf
4. Pawar, A. P., Mankar, S. H.: Crashworthiness evaluation of low weight recyclable intrusion beam for side impact. Int. Eng. Res. J., 1894–1898 (2008)
5. More, K.C., Patil, G.M., Belkhede, A.: Design and analysis of side door intrusion beam for automotive safety. Thin-Walled Structures **153**(1–3), 106788 (2020)
6. Jeyakumar, P.D., Devaradjane, G.: Improvement of the frontal structure of a bus for crash accidents. Transp. Syst. **11**, 183–187 (2012)
7. Regulation No 95 of the Economic Commission for Europe of the United Nations (UNECE) — Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants in the event of a lateral collision [2015/1093]., https://op.europa.eu/en/publication-detail/-/publication/a223bf6e-26c6-11e5-a342-01aa75ed71a1
8. Heiko, J., et al.: Review of the development of the iso side impact test procedure for child restraint systems. In: 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Lyon, France, June 18–21 (2007)
9. Karlinski, J., Ptak, M., Dzialak, P., Rusinski, E.: Strength analysis of bus superstructure according to Regulation No. 66 of UN_ECE. Arch. Civil Mech. Eng. **14**(3), 342–353 (2014)
10. Li, Y., Lan, F., Chen, J.: Numerical study on the influence of superstructure configuration on coach rollover resistance performance. Int. J. Crashworthiness **17**(6), 637–654 (2012)
11. Na, J., Wang, T., Wu, C., Yan, Y.: A four-node membrane element model with bending modification for one-step algorithm for bus rollover impact. Eng. Comput. **32**(3), 607–620 (2015)
12. Marianski, M., Szosland, A.: Research on the strength of Standard bus bodies at rollover on the side. Technikal University of Lodz, pp. 29–41 (2012)
13. Noaimadudin, W.M.K., Nor, H.S., Amir, R.A.G., Nik, R.A., Khairul, I.A.J.: Modelling and simulation of a single deck bus subjected to rollover crash loading. Appl. Mech. Mater. **393**, 453–459 (2013)
14. Lukaszewicz, D.H.-J.A.: Automotive Composite Structures for Crashworthiness, BMW AG, Research and Innovation Centre, Knorrstrasse 147, 80788. Munich, Germany (2013)
15. Rafukka, I.A.: Numerical investigations in to crashworthiness characteristics of steel conical tubes. Nigerian J. Technol. **37**(2), 663–667 (2018)
16. Xu, T., Liu, N., Yu, Z., Xu, T., Zou, M.: Crashworthiness Design for Bionic Bumper Structures Inspired by Cattail and Bamboo. Applied Bionics and Biomechanics (2017)
17. Jacob, G. Ch.: Automotive Crashworthiness of Adhesively Bonded Carbon Fiber Polymer. Composite Structures, 245 p. (2006)
18. Cebon, D.: Handbook of Vehicle-Road Interaction. CRC Press. 616 p. (1999). ISBN 9789026515545