RESEARCH ON THE STRENGTH OF STANDARD BUS BODIES AT ROLLOVER ON THE SIDE

MICHAŁ MARIAŃSKI[1,] ANDRZEJ SZOSLAND[2]

Technical University of Lodz

Summary

The work was undertaken to investigate the strength of a tourist bus body during rollover on the side or the roof. The investigation of the process of impact against the road surface with simultaneous deformation of body framework will make it possible to assess the safety of bus occupants and the strength of bodies of vehicles of this type. The need to undertake this work arose from the fact that at present, bus bodies do not provide adequate passenger safety in spite of meeting the requirements of current EU regulations.

The investigation of the process of impact against the road surface with simultaneous deformation of body framework has been supplemented with research on the dynamics of impact of various profiles with shapes identical to those of real bus bodies.

Keywords: motor vehicles, buses, construction.

1. Introduction

The analysis of effects of road accidents shows that the accidents with vehicle rollover are among those considered most severe. In more than 90% of cases, the rollover takes place outside of the road surface, when the vehicle goes off the roadway onto the road shoulder. Predominantly, the vehicle bodies being in various positions hit completely random obstacles.

Accident statistics confirm that the most dangerous incidents are those with rollover of vehicles of high total mass, i.e. goods vehicles and buses. If a goods vehicle rolls over, the consequences are in most cases limited to material losses, while in the case of a bus,

[1] Technical University of Lodz, Department of Vehicles and Fundamentals of Machine Design, 116 Żeromskiego Street, 90-924 Lodz

[2] Technical University of Lodz, Department of Vehicles and Fundamentals of Machine Design, 116 Żeromskiego Street, 90-924 Lodz, e-mail: andrzej.szosland@p.lodz.pl, ph.: +48 42 636 24 00

the life of about a dozen or even more people is very often in danger. Big deformations of the bus roof or sidewall are very dangerous for the occupants. Since 2002, bus accidents of exclusively this type have resulted in more than 100 deaths and over 1 000 injured in Europe only.

The vehicle framework should absorb the impact caused by vehicle rollover so that the kinetic energy of the impact is converted into structure deformation work. Understanding this problem, bus body designers should endeavour to improve passive safety of the bus body by applying appropriate structural design solutions. Bus bodies may be much safer for the passengers if the body absorbs an appropriate part of the energy of impact against the obstacle. Theoretically, this corresponds to a structure that would constitute an energy accumulator thanks to the deformation work.

A typical vehicle used for passenger transport is now a 2- or 3-axle high-decker coach, 10 to 14 m long. The body of such a bus is characterised by high rigidity of its lower part, which accommodates transmission system, suspension system, and axles, and significantly lower rigidity of the part with the passenger deck, where the body structure consists of walls and roof only. Such a design is dictated by the necessity to provide adequate spaciousness and height of the bus interior and good field of vision for the passengers. The current requirements regarding the rollover impact strength of bus bodies are laid down in UN ECE Regulation No. 66, which is an annex to EU Directive No. 2001/85/EC of 20 November 2001 [1], entitled "Strength of superstructure." This annex covers special regulations applicable to vehicles used for the carriage of passengers. These requirements, however, are far from being sufficient for adequate passive safety to be secured. The provisions of the Directive do not prevent real accidents. This is confirmed by the sad statistics of accidents with fatalities where buses meeting these requirements were involved.

Fig. 1. Example of an actual bus overturn, where 19 people were killed near Lake Balaton in Hungary on 1 July 2002 (photo: PAP)

If the conditions of impact of the bus body against the ground are mild and the bus rolls over onto a flat surface then it is quite likely that there would be no casualties. However, when the bus rolls over onto an uneven ground with protruding obstacles or if a part of the bus body hits the outer edge of the roadside ditch (as it most frequently happens, see Fig. 1), such an accident usually ends in fatalities. This is due to the following:
- Significant displacements of sidewalls;
- Unfavourable deformation of the bus body, with breaks of load-bearing elements;
- Separation of body truss members (window pillars);
- Falling out of passengers directly under the vehicle.

2. Requirements regarding the rollover impact strength of the bus superstructure, to UN ECE Regulation No. 66

In result of research work carried out in Europe in 1987, UN ECE Regulation No. 66 was worked out, which defined the bus body strength requirements to be met during vehicle rollover. According to this document, the superstructure should absorb the energy of impact caused by vehicle rollover and the resulting deformation of the superstructure should not result in disturbing the minimum survival space for the passengers and the driver.

According to the Regulation, the bus superstructure strength should be checked to one of the following methods:
- Rollover test on a complete vehicle;
- Rollover test on a body section representative of the complete vehicle structure;
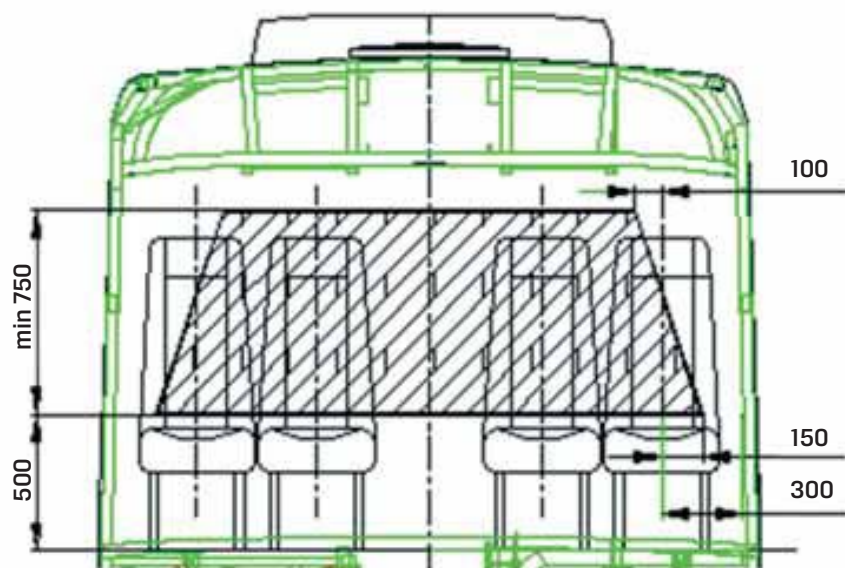

Fig. 2. Minimum survival space for passengers, to UN ECE Regulation No. 66 [1]

- Pendulum test on an appropriately selected part of the bus superstructure or an appropriate group of vehicle parts;
- Verification of superstructure strength by calculation.

The checks carried out to various methods are aimed at investigating the degree of deformation of the vehicle body to determine the survival space for the passengers. This space, as a part of the original space inside the vehicle, should not be less than the hatched area in Fig. 2.

To carry out the rollover test on a complete vehicle, a production bus submitted by the manufacturer is used as a test specimen. The vehicle should be in running order, i.e. it must be provided with fuel, all operating fluids, lubricants, standard tools, and spare wheel. Conversely, any load that would simulate the passengers should not be included in the vehicle mass. The bus is placed on a tilting platform. The tilting speed of the platform should not exceed 5°/s (0.087 rad/s), thanks to which the vehicle may be tilted with no dynamic effects until it rolls over (Fig. 3).

Fig. 3. Rollover test conditions, to UN ECE Regulation No. 66 [1]
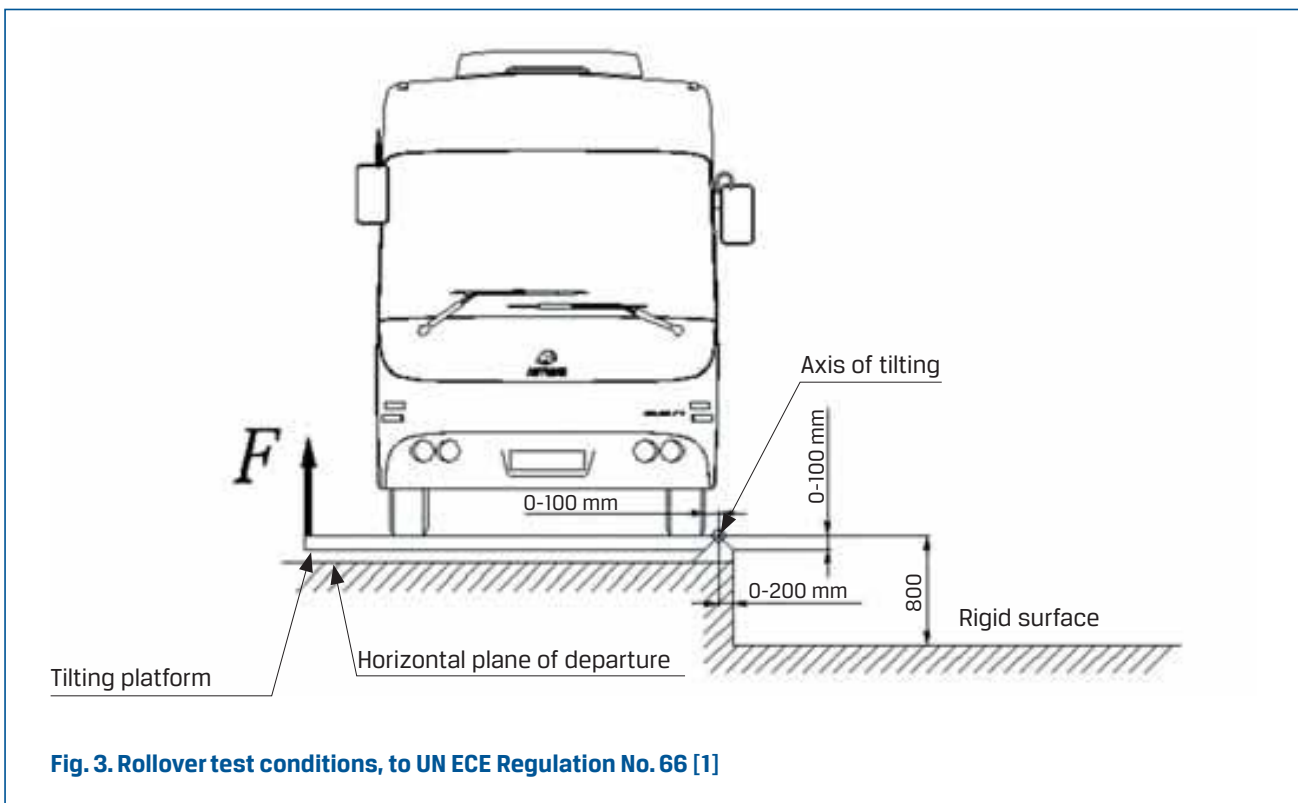
An actual bus rollover test has been shown as an example in Fig. 4

Actual accidents have shown that this Regulation is incorrect for many reasons:
a) This test has a quasi-static nature and it does not represent in any way the dynamic loads that would act on the bus structure during an actual bus rollover accident.
b) The bus is not loaded with any ballast to simulate the passengers; hence, the forces applied to the bus structure are far lower than those actually observed.

Fig. 4. Actual bus rollover test (photo: Scania) [4]

c) The location of the centre of gravity of the bus without load differs from that of the bus fully laden [5].

d) The rollover of a bus section representative to the whole bus structure constitutes a very rough approximation.

e) The results of the calculations made to verify the superstructure strength are also burdened with significant inaccuracies.

An important criterion for the evaluation of bus superstructure strength is provided by the values of the stresses occurring in window pillars and at the places where the pillars are connected with other parts of the load-bearing structure and with the roof. Plastic deformations lead to cracks in the parent metal (or in the weld) at the places where the stresses exceed the ultimate material strength. The breaks in the superstructure truss are particularly dangerous if they occur at the places where the structural cohesion is prerequisite for the structure deformation mode to be correct.

3. Testing of the bus superstructure strength at impacts occurring at bus rollover on the side

The bus motion immediately preceding the rollover on the side is very complex and empirical solutions must be employed to enable adequate mathematical modelling of such a state, which is a result of inputs inconsistent with the intended bus operation mode. When wheels on one vehicle side lose contact with the road surface while the vehicle is tilting to the other side, the nature of cooperation of tyres on the other side with the road surface changes as well. At present, no analytical method of solving this problem is available because of the complexity and random nature of the phenomena occurring at the place of contact between the tyre and the road surface. For an adequate mathematical bus model to be built, a test stand had to be made, on which the lateral force values Fy were experimentally determined for various angular positions of the wheel plane at the place of contact between the tyre and the road surface.
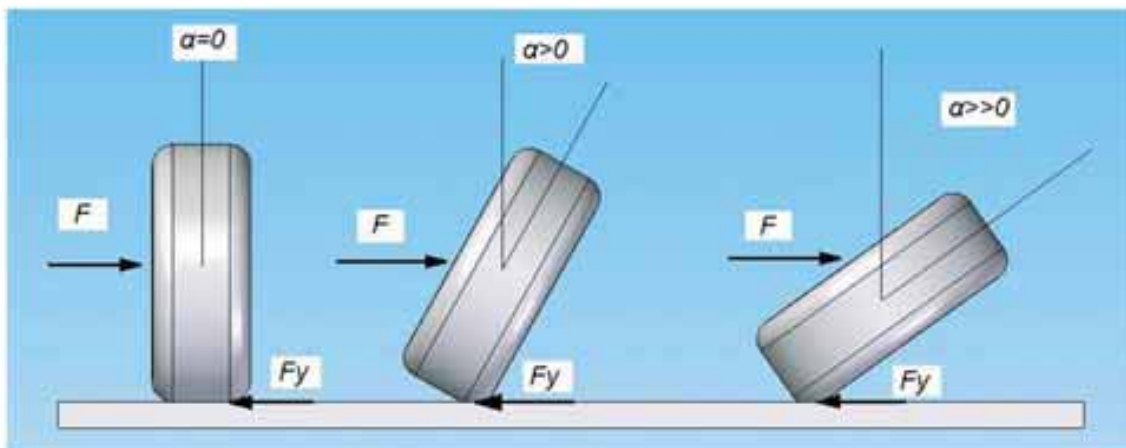

Fig. 5. Illustration showing the behaviour of a pneumatic tyre when sliding sidewards, to depict the test method

The experiments revealed that the lateral force Fy declined with increasing wheel plane tilt angle. At the analysis, a simplifying assumption was made that for $\alpha = 0$ and $\alpha \gg 0$, the wheel was pressed against the ground with a force corresponding to ¼ and ½ of the total vehicle weight, respectively. When α rose from 0 to 18°, the lateral force steeply dropped. This may be explained by decreasing area of contact between the tyre tread and the road surface. When the wheel plane tilt angle α exceeded 18°, the tyre tread lost its contact with the road surface, i.e. the area of contact between the tyre and the ground was shifted to the tread shoulder and tyre sidewall, and the lateral force Fy kept declining, but with a stabilised rate.

Based on the experimental data collected, a computer program was written for simulation rollover tests to be carried out. Mathematical equations were introduced that described

the kinematics and dynamics of the vehicle motion preceding the rollover. With the values of the lateral force *Fy* being known, the vehicle trajectory was determined, the moment of wheel lift-off on one vehicle side was defined, and the speed at which the vehicle equilibrium turned unstable was found. The curvilinear motion of the bus was initiated by a sudden turn of the steering wheel. Obviously, the wheel lift-off depends on the location of the vehicle centre of gravity and on the declared coefficient of adhesion between the wheel and the road surface. The vehicle speed immediately preceding the bus rollover as determined with the use of the computer program was taken as an input for the simulation of impact of the bus body against the non-deformable ground surface. The value of this speed was approximately equal to 20 m/s.

The simulations carried out resulted in the obtaining of a set of data representing the bus response to maximum sudden turn of the steering wheel. The interrelations between changes in the steering wheel turning angle applied as an input and the response obtained in the form of changes in the current vehicle position angle in relation to the starting position depend on many factors, e.g. vehicle design or motion parameters. It was found that the factors of significant importance for the whole vehicle rollover process include linear vehicle speed, wheel-to-road adhesion coefficient, maximum turning angle of the steered wheels (depending on suspension system design), steering wheel turning speed, and values of lateral force *Fy*.

Time histories of the vertical reactions *Fz* applied to each wheel of the bus have been shown in Fig. 6. The bus motion simulation calculations covered the period till the moment when the vehicle equilibrium turned unstable.
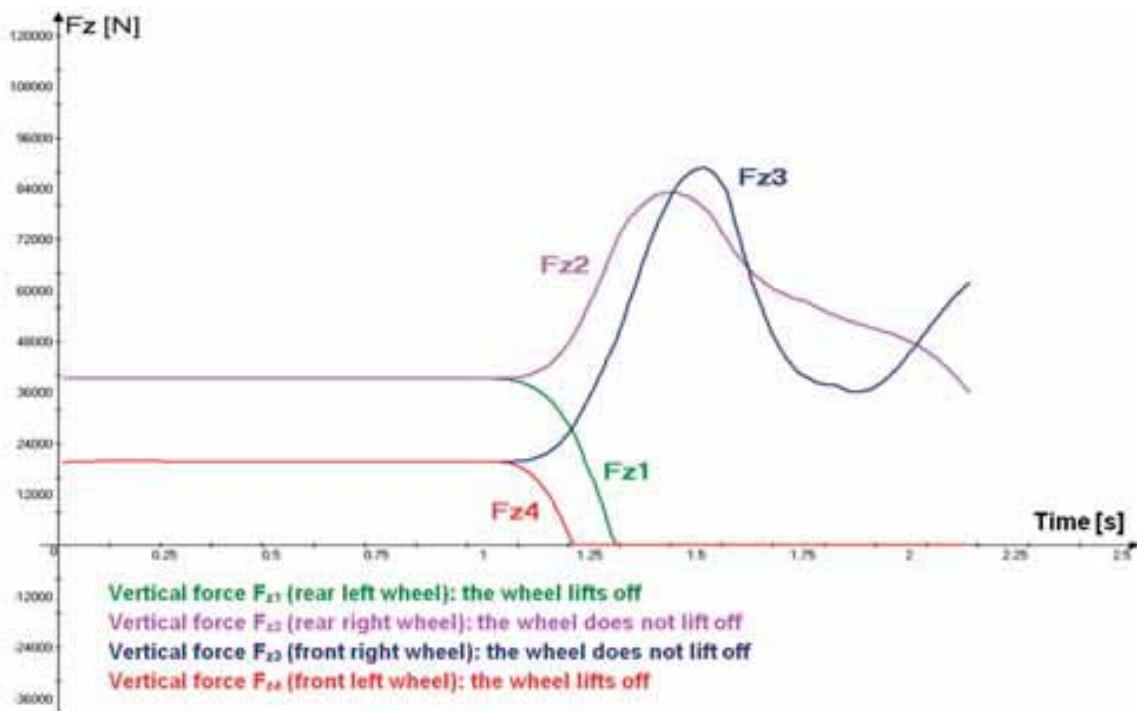

Vertical force F_{z1} (rear left wheel): the wheel lifts off
Vertical force F_{z2} (rear right wheel): the wheel does not lift off
Vertical force F_{z3} (front right wheel): the wheel does not lift off
Vertical force F_{z4} (front left wheel): the wheel lifts off

Fig. 6. Time histories of vertical reactions *Fz* applied to each wheel of the bus

The simulation impact tests on bus superstructures were carried out in two groups. In the first one, elementary models of bus superstructures were subjected to the strength analysis. The models analysed were designed as tubular profiles with circular, elliptic, and square cross-section. The other group covered impacts of real bus superstructures against non-deformable ground.

The actual shape of the cross-section of a complete bus body is close to a rectangle. In functional and economic terms, such a shape is the best possible solution. However, it has no good points in respect of the energy absorption and deformation mode. Simulations of impacts of elementary tubular profiles against rigid ground were carried out and then comparisons were made between the values of maximum displacements and maximum stresses reduced according to the Huber-Mises theory, determined for selected places in the structure. The analysis was carried out for tubes with circular, elliptic, and square cross-section, made of steel with a yield point of Re = 355 MPa. The tubular structure dimensions were selected to correspond to the body dimensions of a bus 12 000 mm long and 3 750 mm high. The impact test was simulated with the use of the ANSYS software and a shell model based on Shell93 elements. The impact parameters corresponded to a situation where a bus with full load runs into a ditch with a speed of 72 km/h (20 m/s) and rolls over on its side. The modes of deformation of specific shapes were also observed at impact simulations with the impact being several times stronger.

The profiles of the highest and lowest energy absorption capability are those with elliptic and square (rectangular) cross-sections, respectively. The elliptic and any elliptic-like profiles are also highly resistant to loading forces and moments of varying values and
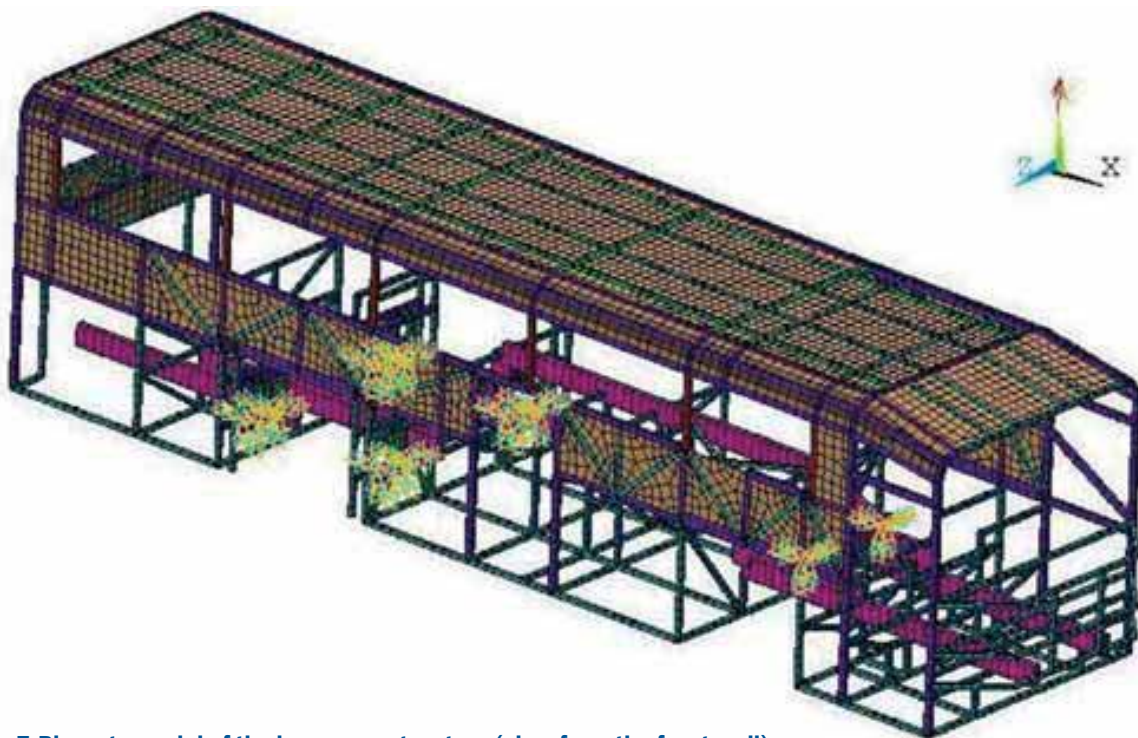

Fig. 7. Discrete model of the bus superstructure (view from the front wall)

directions. For these reasons, bus body design should not be based on rectangular or square cross-section shapes.

Based on engineering design specifications of a tourist bus, a geometric and then discrete model of the superstructure of such a bus was built (Fig. 7). The model constituted a spatial system of beams and shells. It is practically impossible or, at least, very difficult to find a solution for such a structure with using conventional methods. The finite element method (FEM) makes it possible to build a mathematical model of the bus body and to run an impact simulation process for any impact type. Thus, a picture may be obtained that would visualise the deformation of the structure the task of which is to absorb the maximum possible part of the impact energy.

The bus body framework is made of steel tubes of square and rectangular cross-sections, connected together by welding. The dimensions of most of the profiles used are: 60×40×2 mm, 40×40×2 mm, and 60×35×2.5 mm (sidewall and roof elements), and 60×40×2.5 mm and 40×40×2.5 mm (chassis framework elements). The longitudinal beams of the chassis frame are made of channel bars of 200×70×6 mm cross-section dimensions. The bus body panels, made of aluminium and plastics, are glued to the body structure and they were ignored at the strength analysis. The material of the structural parts is corrosion-resisting ferritic steel X2CrNi12, except for the longitudinal frame beams, which are made of general-purpose constructional carbon steel St4SU. The geometrical model was digitalised with linear beam elements Beam4 and shell elements Shell93.

The structure modelled as described above was subjected to a numerical simulation of a bus rollover in the conditions of an actual accident. The displacements of individual nodes of the bus superstructure and the maximum stresses in specific elements of the structure, reduced according to the Huber-Mises theory, were investigated. The strength analysis conditions imposed a requirement that the case of a bus rollover on its left side should be simulated. In result of the accident modelled, the bus sidewall moved into the
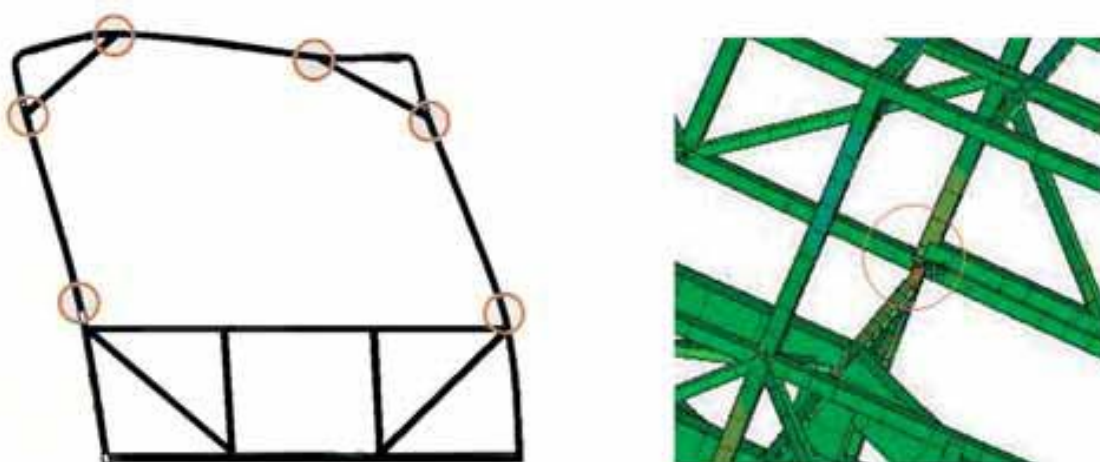

Fig. 8. The places where the stresses exceed the ultimate material strength

bus interior and reduced the passenger survival space. The lower part of the load-bearing structure is very rigid and it practically was not deformed.

A significant impact on the displacement values is exerted by the door openings and large glass panel areas (especially the windscreen). The values of the stresses occurring in specific elements of the bus superstructure constitute another important factor. Plastic deformations lead to material cracks if the stresses exceed the ultimate material strength. For the strength analyses as described above, a material having bilinear characteristics was defined. Results of the simulation based on the use of this material confirmed that the actual ultimate material strength might be exceeded in the areas close to the joints between window pillars and other members of the structure (Fig. 8). The cracks are particularly dangerous if they occur at the places where the structural cohesion is prerequisite for the structure deformation mode to be correct. In this case, this applies to the joints between window pillars and other parts of the load-bearing structure and the roof.

Fig. 9. A model with stiffened rear wall, without roof reinforcements. Contour lines representing the resultant "XYZ" displacements of all the bus body members, viewed from the rear, with reference to the non deformed model

The most important numerical values of the results of simulation of bus body deformations, obtained for different bus bodies, have been tabularised below. The analyses presented above have revealed that none of the current bus bodies is capable to provide adequate passenger safety in the case of a rollover: during such an accident, cracks and breaks emerge, in result of which the correct deformation of the bus body cannot be secured.

Table 1. Comparison of calculation results obtained for bus bodies made of a material of bilinear characteristics and subjected to a simulated impact in conditions corresponding to those of an actual road accident.

| Item	Body shape / internal structural modifications	Maximum resultant displacement "XYZ" [mm]	Maximum displacement in the longitudinal direction (along the "X" axis) [mm]	Maximum displacement in the transverse direction (along the "Z" axis) [mm]	Maximum stress reduced according to the Huber-Mises theory [MPa]
1.	Traditional bus body, with no internal reinforcements	640,382	-155,297 ÷ 136,203	-141,915 ÷ 632,825	733,0
2.	Traditional bus body, with rear wall stiffened by built-in additional structures	553,592	-145,154 ÷ 136,447	-142,333 ÷ 542,765	707,9
3.	Traditional bus body, with roof reinforcements and with no additional real wall stiffening structures	511,003	-153,06 ÷ 136,237	-141,78 ÷ 501,984	726,8
4.	Traditional bus body, with roof reinforcements and with rear wall stiffened by built-in additional structures	478,073	-148,979 ÷ 136,337	-141,987 ÷ 465,386	704,95
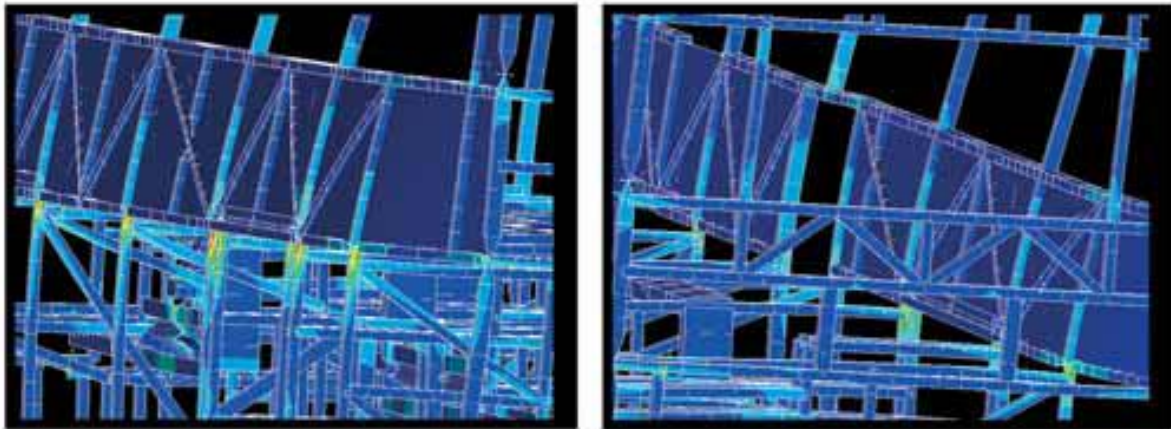
Fig. 10. A model with stiffened rear wall, without roof reinforcements. Contour lines representing the reduced stresses in bus body members. Magnified view of the places of the highest material effort

4. Recapitulation and conclusions

Within this study, actual accidents with tourist buses were analysed where the busses rolled over on the side or on the roof. The provisions of EU Directives regarding the type-approval testing of rollover strength of bus superstructures were also carefully considered. The work carried out has revealed very poor resistance of bus bodies to impacts resulting from bus rollover.

The dynamics of the bus motion immediately preceding the rollover was investigated. Based on experimental tests, the vehicle motion parameters have been determined at which bus rollover may take place (i.e. the stability of motion may be lost).

Simulation tests of the strength of elementary tubular profiles when hitting non-deformable ground surface have revealed that, from the point of view of resistance to impacts and energy absorption, the current rectangular cross-sections of bus bodies may turn out to be dangerous for bus occupants. The results of the simulation strength tests are also applicable to actual bus superstructures. Simulation impact tests were carried out at the same time on hypothetical bus bodies; they have confirmed the finding that bus body frameworks with alternative symmetric circular shapes would provide better safety for bus passengers.

The research work carried out helped to identify the most important quantities that should be known for the bus rollover process to be investigated. Analyses of bus structures made it possible to specify which bus bodywork forms might provide the highest safety standard for bus passengers. The solutions found should serve as guidelines for the next research works and for the future application of the findings in the bus industry. For the passenger safety standard of tourist buses to be adequately raised, a multistage improvement process is required.

References

[1] EU Directive 2001/85/EC of 20 November 2001.

[2] PENG H., EISELE D. D.: *Vehicle dynamics control with rollover prevention for articulated heavy trucks.* 5th Int'l Symposium on Advanced Vehicle Control, August 22-24, 2000, Ann Arbor, Michigan, USA.

[3] Report: *Stan bezpieczeństwa ruchu drogowego oraz działania realizowane w tym zakresie w 2006 roku (Current state of road traffic safety and the actions carried out in this field).* Warszawa, March 2007. A document accepted at the session of the Council of Ministers on 3 April, 2007.

[4] Scania publications in the media: www.scania.com.

[5] PN-ISO 10392:1997: *Pojazdy drogowe dwuosiowe. Określenie położenia środka masy (Two-axle road vehicles. Determination of the centre of gravity).*

[6] ZIENKIEWICZ O. C., Taylor R.: *The finite element method.* McGraw-Hill, Berkshire, England 1991.

[7] RUSIŃSKI E.: *Metoda elementów skończonych (The finite element method).* WKŁ, Warszawa 1994.

[8] FRĄCKIEWICZ H.: *Wytrzymałościowe studium cienkościennych ustrojów samochodów ciężarowych i autobusów. Cz. I i II. (Material strength study on thin-walled structures of commercial vehicles. Part I and II).* A study report prepared to commission of the Institute of Fundamental Technological Research of the Polish Academy of Sciences, Kielce 1975.

[9] KLEIBER M., WOŹNIAK C.: *Nonlinear mechanics of structure.* PWN, Warszawa 1991.

[10] ZIELIŃSKI A.: *Konstrukcja nadwozi samochodów osobowych i pochodnych (Construction of bodies of passenger cars and car-based vehicles).* WKŁ, Warszawa 1998.

[11] *Bus Rollover Accident Simulation.* SAE Paper No. 790994.

[12] LANZENDOERFER J., SZCZEPANIAK C., SZOSLAND A.: *Teoria ruchu samochodu (Theory of motion of the automotive vehicle).* A textbook of the Technical University of Lodz, Łódź 1980.

[13] MITSCHKE M.: *Dynamika samochodu (The dynamics of the automotive vehicle).* WKŁ Warszawa 1977, the 1st issue.

[14] WICHER J.: *Bezpieczeństwo samochodów i ruchu drogowego (The safety of automotive vehicles and road traffic).* WKŁ Warszawa 2002, the 1st issue.

[15] ZIELIŃSKI A.: *Konstrukcja nadwozi samochodów osobowych i pochodnych (Construction of bodies of passenger cars and car-based vehicles).* WKŁ Warszawa 2007, the 3rd issue, updated.

[16] MARIAŃSKI M.: *Badania wytrzymałości nadwozi autobusów na uderzenia zachodzące przy bocznym przewróceniu się pojazdu (Testing of the bus superstructure strength at impacts occurring at bus rollover on the side).* Doctor's dissertation, Łódź 2009.

[17] RUSIŃSKI E., KOPCZYŃSKI A.: *Bezpieczeństwo bierne, pochłanianie energii przez profile cienkościenne (Passive safety; energy absorption by thin-walled profiles).* Oficyna Wydawnicza Politechniki Wrocławskiej (Publishing House of the Wrocław University of Technology), Wrocław 2010.