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COMPLIANCE ASSESSMENT OF THE SUPERSTRUCTURE OF BUSES IN ACCORDANCE WITH THE REQUIREMENTS OF REGULATION NO. 66 ON THE BASIS OF COMPUTER SIMULATION OF TESTS

The existing approaches of domestic and foreign researchers in the field of simulation of the loading of bus frames with the calculation evaluation of the superstructure are considered for compliance with the requirements of passive safety during rollover. The criteria and the main ways to improve the quality of computer models and to reduce the duration of calculations are determined. The fundamentals of the methodology for computer simulation of bus tests are presented and described for compliance with the requirements of Regulation No. 66. Revision 1 — Amendment 2. Uniform technical prescriptions concerning the approval of large passenger vehicles with regard to the strength of their superstructure (hereinafter — Regulation No. 66). An example of computer simulation of testing the superstructure of a suburban bus during rollover is given using the ANSYS LS-DYNA finite element analysis software system. Preparation of the model is performed using the LS-PrePost program.

Keywords: *superstructure, bus, passive safety, computer model, finite element analysis, tilting angle, tilting platform, moment of inertia, initial angular velocity, potential impact energy, Regulation No. 66*

Introduction. Amongst the key requirements for superstructure of bus body is its safety requirements. These requirements are the ability of the structure to maintain the necessary flail space in the passenger compartment to minimize the driver and passengers' injury during a potential road traffic accident (RTA). In the countries acceded to the Geneva Accord of 1958, Regulation No. 66 [1] applies to the safety requirements for structures of bus bodies. The document regulates carrying out and analysing the results of tests on research on rigidity and strength of the body properties. Currently, Regulation No. 66 applies to the bodies of passenger vehicles in the Republic of Belarus.

Modern achievements in the field of numerical methods of solving problems of deformable body mechanics, carried out in the form of computational software complexes on the one hand, and the presence of high-efficiency multiprocessor workstations, the possibility of combining computational resources within a network in the form of clusters on the other hand, as a whole allow to address the analysis tasks on high-rate dynamic process within a short time frame taking into account the real geometry of the object of study, a detailed description of the contact interaction, non-linear material properties, failure criteria, equation of materials state, etc.

An important aspect of development relevance of computational methods of body structure conformance assessment to safety requirements is that the Annex 9 of Regulation No. 66 already allows to make replacement of field tests by virtual ones with sufficient volume of substantiations of credibility of calculations.

The finite elements method in an explicit formulation is the most widely applied method for solving problems of computer simulation of dynamic loading of vehicle structures in practice. However, it is necessary for high-performance computational tools to have methodological supply for the preparation of the computational model. Therefore, the urgent task is to develop methodological recommendations and approaches to assessing the superstructure of a vehicle using numerical methods that minimize the use of time of the given process and ensure the reliability of calculation results while fulfilling the requirements of the Annex 9 of Regulation No. 66 [1].

Analysis of known approaches in the field of computer simulation of testing of the bus superstructure during rollover. There are two stages of the process of carrying out computational researches. The first one is the preparation of a computational model; the second is the calculation itself. Thus, the first stage is characterized by the longest execution time. This is due to the transformation of the initial geometrical model, configuring and setting the source data, conducting additional verification studies. Hence, the task of the researchers and calculators is to prepare adequate and reliable computer models, allowing to obtain an assessment of the structural strength indicators in minimum terms and with sufficient level of reliability. The authors of the work [2] during virtual rollover tests of the body of the GolAZ-5290 bus and its separate sections in order to reduce the machine calculating time, initially set the frame construction material as absolutely rigid, and at the moment of the collision with the bearing surface it switched to the deformable one.

One of the topical and the most comprehensive works on the assessment of passive safety of buses is the thesis work of P.S. Rogov [3]. The author analysed and computed the bus models, taking into account the trim of the body, seats and handrails. It is shown that the presence of these elements can reduce the calculated value of deformation of the body pillars up to 20 %. The loading simulation was carried out by preliminary turning of the bus to the bearing surface, giving it an angular velocity corresponding to the moment of collision with the bearing surface. Furthermore, to determine the angular velocity at the moment of impact the bus was viewed upon as a material particle, and its moment of inertia was determined by multiplying the mass by the square of the distance to the rollover axis.

The loading of beam and shell models of frame sections according to quasistatic principle was studied in the work [4]. The calculation results showed that a simplified (beam) finite element model has a higher load-bearing capacity (by 10–30 %) than a similar detailed model consisting of shell elements. This is due to the impossibility of beam elements to describe the loss of section shape due to large plastic deformations.

One of the methods used to simulate the rollover process is to simulate the impact loading of a bus body with a turntable [5]. The authors note that such a loading mode is more severe and damaging in comparison with the actual rollover of the bus, since it does not take into account the possibility of its sliding off the flange of the tilting platform and collision with the bearing surface over the entire sidewall area.

Comparison of the results of field and virtual tilting of the frame section was conducted in this work [6]. The calculations were performed using the ANSYS LS-DYNA software. The turntable and ballast box were modelled as absolutely rigid bodies. The CONSTRAINED_EXTRA_NODES_SET option was used when connecting the ballast box, bearer and sections to each other. All structural elements of the model consisted of shell elements. The section material with a given curve of plastic hardening during the calculation until the section came into contact with the bearing surface was set as absolutely rigid, and then switched to the deformable one. The construction material was set using the bilinear material model MAT_PLASTIC_KINEMATIC. It is noted that the counting time can be reduced by 10 or more times when switching the properties of the material.

The testing process consists of two stages: rollover, where the structure gains energy, and the impact itself. Consequently, the use of software systems for the study of kinematics and dynamics of multi-component mechanical systems (MultiBody System or MBS), in particular, the MSC.ADAMS software package was widely used among domestic and foreign researchers to calculate the first stage of testing. The bus superstructure design is calculated as a system consisting of rigid bodies and kinematic joints/pairs with the specified hardening characteristics and the orientation of the rotation axes in space. The authors of the work [7] conducted a comparison of MBS and finite element simulation through dynamic loading of a cantilever fitted pipe. A good match of the results has been obtained. However, when using MBS, it is necessary to have position coordinates, stiffness characteristics, and orientation of the rotation axes in the kinematic pair space.

The joint use of software systems for dynamic kinematic research and FEM for calculation of bus frames for safety was applied in work [8]. The MSC.ADAMS software package was used to determine the kinematic and dynamic parameters of a bus fall. The bus was modelled as a parallelepiped. The obtained values of the falling speed were set in the calculated finite element model in the LS-DYNA package, where the bus was preliminary turned to the bearing surface in a position corresponding to the moment of impact. The joint use of software systems made it possible to describe the rollover process with high reliability.

The passive safety assessment of a tourist bus using the LS-DYNA program is demonstrated in the work [9]. The characteristics of the frame material were set using the multilinear model MAT_24 PIECEWISE_LINEAR_PLASTICITY_MODEL, bus units were given properties of absolutely rigid bodies. The bus was preliminary turned to the impact surface until it came into contact with it during the simulation of the loading.

The impact energy was determined by the formula:

$$E = 0{,}75 \cdot M \cdot g \cdot h, \tag{1}$$

where M — the mass of the bus; g — the gravitational acceleration; h — the vertical displacement of the vehicle's center of gravity (CG) during rollover.

The angular velocity at the moment of the beginning of the contact of the bus with the bearing surface was determined after calculating the impact energy.

A similar method is described in the work [10]. The peculiarity of this work is that when calculating the kinematics and dynamics parameters of the bus fall using multi-component simulation software, body torsion using stiffness factors, suspension characteristics and rigidity of tires were taken into account.

In the work [11], the simulation of the tilted section was performed using a combined method. The pillars are modelled as canes, and the roof, floor and trim are in the form of shells. This approach is aimed at reducing the machine calculation time.

The authors described their own way of reducing the calculation time in their work [12]. The body section was modelled as a beam frame with elastic elements having nonlinear characteristics. The characteristics of the elastic elements were set on the basis of axial, bending and torsional destructive loads of structural elements of the frame.

The passive safety assessment of buses using the RADIOSS software is reflected in the work [13]. The loading of the bus was simulated by turning it to the impact surface with the corresponding setting of rotation center and angular velocity. This work uses a detailed finite element model of the bus, including glass, panels, headlights, and detailed wheel models.

Thus, the above works show that the main criteria for assessing the quality of calculation models are reliability and total duration of calculations. In turn, the total duration of calculations consists of the time spent on preparation of the model and the computer calculation time. Moreover, the first component is the most time consuming. First of all, it depends on the method of preparation of the calculation model, the possibilities of organization of preparation, as well as the software, which allows realizing the necessary functions of model preparation.

In order to reduce the machine calculation time, tests are carried out on separate sections of the frame, beam and combined models are used. There are also used the material switching from absolutely rigid to deformable and the turning of the bus to the impact surface or simulating the impact loading of the turntable before calculating.

The reliability criterion for a computer model of the bus superstructure, as a rule, is a compliance of calculated and experimental values of the indexes controlled during physical tests, namely, movements of side pillars of the bus after its rollover. Improving the reliability of the calculation results is provided by modelling the trim of the frame, handrails and seats, setting the exact location of the CG, conducting research of the bus fall kinematics by means of multicomponent simulation systems.

Based on the results of the analysis of works, it is proposed to apply the following recommendations aimed at reducing the calculation time while ensuring high requirements for the reliability of the results:

- ensuring a high level of accuracy in identifying the parameters of material models;
- taking into account the uneven distribution of strength properties in structural elements;
- using a model with distributed masses, when studying the kinematics of a bus fall;
- using guidelines for model preparation;
- determining the parameters of the rollover of the bus in software, which prepare the model directly;
- using the method of preliminary turning of the superstructure of the bus to the impact surface before it is loaded.

Computer simulation of rollover tests of the bus superstructure in accordance with the requirements of Regulation No. 66. Taking into account the experience of the previously performed work on simulating the tests of buses superstructures, as well as the works of domestic and foreign researchers at the Republican Computer Center of Mechanical Engineering of the Joint Institute of Mechanical Engineering of the National Academy of Sciences of Belarus, methodological approaches to the preparation of a bus model for computer simulation of superstructure tests according to the requirements of the Regulation No. 66 have been developed and applied. The main stages of preparing the model of the bus superstructure are given below:

- collection and preparation of initial data for computational research:
  - properties of materials, structural elements, validation of properties [14];
  - design CAD-model (superstructure, frame, front axle, rear axle, engine, transmission, cooling system, fuel tank);
  - technical description (coordinates of the CG, the value of the curb and gross weight of the bus, the number of seats);
  - mass characteristics of units and assemblies;
- geometrical model preparation;
- creation of finite element models;
- quality control and adjustment of the finite element mesh;
- addition of symmetrical parts of structures to the initial composition (operation "mirror");
- setting properties and settings for finite element models of assembly units;
- creation of necessary connections and links between structures;
- assembly of the general finite element model of the bus;

- creation of connections and links between models of the assembly units;
- addition of models and location of contact surfaces;
- specification of initial, boundary and contact conditions;
- specifying information output parameters and preparing the initial model file for launching the solution;
- calculation;
- analysis of the calculation results;
- specification of the calculation model (if necessary):
  • modelling of panels, handrails, seats;
  • glasses modelling;
- calculation;
- analysis of the calculation results.

According to the presented stages, the initial data for the beginning of works is a design solid geometrical 3D model of the bus superstructure and structures, which includes frame, sheathing panels, glasses, seats, chassis (if frame structure), joints and units. The coordinates of the CG, corresponding to the equipped state of the bus should be given in the initial data for work. The document on the mass characteristics of joints and units shall contain information on the mass values of the main components of the bus. The CAD model of the bus is presented in a file containing general assembly of bus parts and structures. Depending on the license settings of the software, it can be a specialized CAD package file, or a parasolid, iges, step, etc., supported by the interface of a graphical preprocessor of finite element analysis program.

In order to minimize the complexity in the considered process of preparing the calculation model, the use of previously developed assemblies and structures applied in the studied bus is provided. Therefore, at the given stage assembly units or structures, models of which are already available according to the results of previous researches, if any, are determined and excluded from consideration.

At the second stage, CAD model of the bus is divided into the assembly units consisting both of separate structures and groups of structures (assemblages). This is an important moment of work. Starting from this stage, various specialists can simultaneously carry out the most time-consuming work both in time and in resources. At the same time, the project manager has the opportunity to distribute the tasks according to complexity and the qualifications of the employees. It allows to considerably reduce the preparation time of preparing geometrical models.

The CAD model is divided into assembly units based on the layout and technological solutions of the bus, allowing to minimize labor input of assembling and setting the properties of the general settlement model. The assembly units are formed, consisting of both separate structures and groups of structures united by functional or technological characteristics. It should be noted that the number of assemblages or separately allocated structures does not depend on the number of performers. The positive effect of division is reached by simplification of the organization and work execution, as well as monitoring the entire process of its implementation.

As it has been mentioned above, since the general model is represented by assembly units, part of the structures or assembly units, and consequently their finite element models, passing unchanged from previous bus variants, can be used from previously completed works, or, on the contrary, in the subsequent works. It significantly accelerates the process of research and seeking new solution and brings the design process to a higher, system level.

The following stage is the preparation of design geometrical 3D models. As mentioned above, work is carried out in parallel on CAD models of separate structures or formed assembly units of structures. We will present the main operations performed, considering special labor input of this stage:
- removal of redundant geometrical objects from the model that do not affect the processes under research;
- selection of structures and details having symmetry planes and their separation (“cutting”) along these planes with the removal of redundant information for further work with reduced data volume;
- the conversion of structures made of thin-sheet material, represented by volume solid-state geometry, in the surface (the allocation of the middle surfaces);
- simplification of the geometry (removal of geometric elements with relatively small geometric dimensions such as holes, fillets, chamfers, technological elements, etc.);
- separation (“cutting”) of geometrically complex parts and structures into simpler ones in order to ensure control over the creation of a computational mesh;
- checking and providing connections of constituent parts of a single structural element to each other;
- elimination of mutual intersections of structures and model parts;
- creation of simplified geometrical models of fasteners (bolts, rivets, etc.);
- specifying the location of spot and seam welding (if not present in the original CAD model).

At the next stage, based on simplified and converted geometrical 3D models, the creation of finite element models of bus structures is performed. When creating a mesh, it is recommended to use 4 knot shell and 8 knot volume elements of the non-degenerate form. The use of elements of a degenerate form in combination with reduced integration schemes can adversely affect the accuracy of the calculation results.

Mesh generation is carried out with strict requirements for minimum element sizes. This is due to the fact that with an explicit integration scheme, the calculation step time is described by the Courant–Friedrichs–Lewy condition and means that this step should take less time than the process of the deformation wave passage through the element [15]:

$$\Delta t \leq \frac{l_c}{c},$$

where Δt — the time step; l_c — the typical element size; c — the sound velocity in medium (material).

From the dependence it follows that a decrease in the size of an element leads to a proportional increase in the duration of the calculation process (without changing other parameters). On the other hand, a large mesh describes the shape of the structure incorrectly, and, consequently, its deformations and stresses in the areas under consideration. Taking this into account, the recommended size of a shell element when simulating the most loaded elements of the bus may be 8–10 mm. In this case, the time step for steel structures will be about 0.6–1 μs. Thus, at this stage, the task is to obtain a uniform regular mesh of a given size for the model structures.

The quality control of the finite element mesh is performed, as described above, firstly by the criterion of the element size and secondly by a set of criteria such as the aspect ratio of the element sides, Jacobian, taper, skew, warpage, presence or ratio of elements of a degenerate shape to the total number of elements, etc. When finding elements that do not meet the requirements, the model correction of the found deviations is performed.

After receiving finite element models that correspond to the set requirements, the general setting of properties and settings of all components of the model is carried out. It consists of performing following operations:
- description and assignment of material properties;
- setting the thickness of the shells;
- selection of description formulations and integration features of the elements used;
- setting properties describing spot, seam welding and other types of joints;
- description of elastic and damping properties of suspension elements.

It is recommended to describe material properties using material models that describe nonlinear properties and allow to set fracture criteria. In this case, preference is given to the parameters of the models obtained from field tests of material samples or research of structural elements.

At the next stage of model preparation, a number of operations on addition and association of symmetric parts of designs to their complete structure is carried out. Thus, all the work on improving the geometry and the finite element mesh, performed in the previous stages, is carried out with a significantly reduced volume, which allows to reduce the duration of these stages of the model preparation process by up to two times.

Next, the necessary connections and links between the structures contained in separate groups are created. Thus, welded, bolted, riveted and other joints; contact pairs; kinematic connections, etc. are created and described.

In order to check the adequacy and operability (verification) of the created models and connections, calculations are carried out according to simplified loading schemes. The task of such calculations is to reveal possible inaccuracies and problems of the created models. It allows significantly simplify and minimize labor input of more difficult stage of completion, search and correction of inaccuracies of the general model of the bus. An example of such calculations is a modal analysis, which allows to identify poorly fixed parts of the model.

As the models of assembly units are ready, they are combined into a general finite element bus model. Similarly to working with assembly units at this stage, the creation of the necessary connections and links only between the given groups of structures is performed.

After preparing the general model of the bus, the models of the impact surface, tilting platform, residual space and passengers are added and positioned in space according to the requirements of Regulation No. 66. Initial and boundary conditions providing the necessary values of the force impact energy and the kinematics of the bus motion, as well as the conditions of its contact interaction with the impact and bearing surfaces, shall be specified.

In order to save the information, necessary for subsequent analysis, during the calculation on the hard disk, the duration of the calculation, the parameters of information output are set. This information contains the processes of changing the indicators of interest in the given volume and with a certain periodicity. The source file of the model with all its settings and the solution ready to be launched is recorded.

Then a series of trial (verification) and short duration calculations is performed, the results of which are used to check the correctness of the links, initial and boundary conditions, settings of interaction of assembly units of the model and contact surfaces, possible inaccuracies are identified and appropriate corrections are made.

Once confirmation of the adequacy of the model behavior is received, test simulation is started. If possible, the results are analyzed during the calculation in order to determine the moment when the initial kinetic energy of the impact and the forced shutdown of the calculation are completed by the bus.

At the final stage of the research, post-processing treatment and analysis of the calculation results are performed. According to the deformed after impact bus superstructure, the analysis of the residual space is carried out. At the same stage the most loaded details and elements of the bus superstructure are defined, zones of localization of plastic deformations, places of destructions, if any, are investigated.

Depending on the modelling task, a conclusion on compliance of the bus superstructure with the requirements of Regulation No. 66 is given, or recommendations on improving the bus structures and technologies with the subsequent estimated assessment of their efficiency are made.

Testing the proposed methodological recommendations on the example of a suburban bus. We will demonstrate the proposed methodological recommendations on preparation of bus models for virtual testing according to the requirements of Regulation No. 66 using the superstructure of a suburban bus as an example.

The process of preparation of computer models, calculation and analysis of results were carried out in the ANSYS LS-DYNA (an integrated version of the LS-DYNA solver program in the ANSYS Workbench software package) and LS-PrePost software. The description contains the main used options and settings.

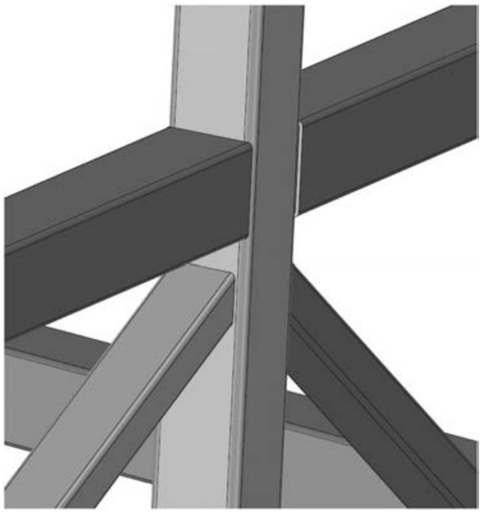
The solid-state design CAD model of the studied bus was divided into the main assembly units: basic structure, frame, if any, wheels, joints and units. Since the basic structure as a whole is made of beams having certain cross-sectional dimensions and wall thickness, the existing volumetric geometrical design model of the frame was converted into a shell one to create a finite element model. In zones of welded joints, it is possible to set the properties of a welding material and thickness of the welded seam, fracture criteria. Shell elements can reduce the total number of degrees of freedom, while maintaining the reliability of the result and reduce the calculation time. A fragment of the solid-state model of the structure and the shell model developed on its basis are shown in Figure 1.

Models of joints and units reproducing mass inertia characteristics were created by volumetric bodies, and passengers were modelled by solid-state ballasts.

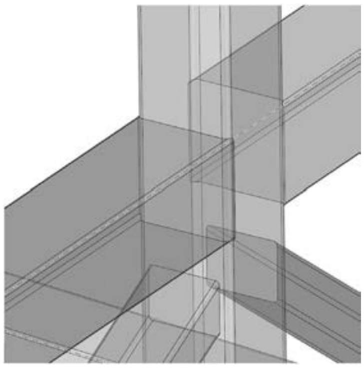
The creation of finite element models was carried out in the ANSYS Workbench software package. At the initial stage, the Virtual Topology tool was used for structures with geometry consisting of complex surface combinations. This tool allows them to be combined and thereby ensure a higher quality of the created mesh by eliminating the generation of elements with small linear dimensions.

Shell finite element models were created with a predominance of tetrahedral elements. The Quadrilateral dominant method was used for this purpose. When describing the requirements to the size of the generated elements, strict (Behavior — Hard option value) requirements were set to comply with the specified values. The dimensions of the faces of the elements were set from 8 to 10 mm depending on the load and the value of the predicted plastic deformations, as well as the features of the geometry of the structure. Smaller dimensions corresponded to more loaded and complex in terms of shape parts and vice versa.

To reduce the estimated time, the bus model was set to the position corresponding to the beginning of contact with the impact surface, and then the corresponding kinematic characteristics were set. The rotation of the bus model is carried out in two stages. At the first stage, the angle of rotation of the bearing surface α is determined whereby the bus reaches the position of unstable equilibrium. At the second stage, the angle β at which the bus touches the impact surface is determined. Figure 2 shows a scheme for determining the angular data geometrically in the ANSYS software package.



a



b

Figure 1 — Variants of three-dimensional geometrical models of a fragment of a bus frame: *a* — volumetric; *b* — shell

The created finite element models for quality control and possible adjustment were transferred to the LS-PrePost program. A text structured model file (k-file), which is used for further initialization of the solution by LS-DYNA program, was generated for this purpose.

LS-PrePost pre- and postprocessor has effective means for analyzing the finite element model mesh and its subsequent adjustment. During the mesh analysis by

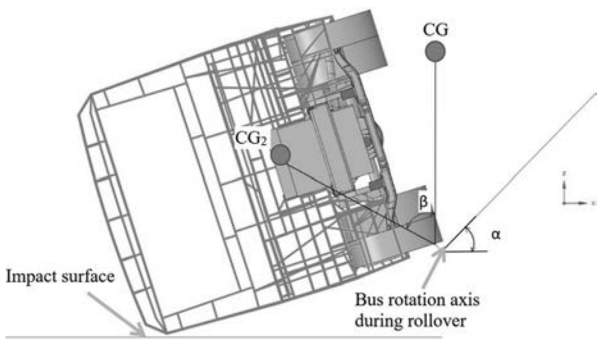


Figure 2 — Scheme for determining the tilting angles and the unstable equilibrium position of the bus

means of LS-PrePost, despite the requirements specified during its creation, elements of poor quality were found. With a large number of such elements, mesh was improved in the ANSYS Workbench software package by changing the topology of the geometrical model. Local adjustments of the computational mesh by direct movement of separate joints, or by the removal and generation of new elements were carried out directly in LS-PrePost.

After reaching the specified requirements for the finite element mesh of models, structures with symmetry were supplemented to the full geometry by applying a mirror image and combining matching joints in the symmetry plane.

The description of properties of structural materials susceptible to plastic deformation was carried out using a bilinear material model with kinematic hardening *MAT_PLASTIC_KINEMATIC, as well as a multilinear model *MAT_PIECEWISE_LINEAR_PLASTICITY. The properties of absolutely rigid material MAT_RIGID were assigned to the solid models of joints and units. The impact surface and the tilting platform were likewise modelled as rigid bodies, with the additional option of limiting movement in all directions. Since the bus is equipped with seat belts, the mass of passengers [1] was taken into account in the calculation model. The passengers were simulated with the solid ballasts. Due to the fact that there is a rigid connection between the passenger models and the frame, the mass of each passenger is assumed to be equal to half the regulated mass and amounts to 34 kg, as described in the current Regulation No. 66.

The additional mass, which includes the mass of the missing in the model elements of the bus body was distributed over the height of the frame to ensure that the calculated value corresponds to the CG specified in the technical description. The distribution was carried out by proportional change in material density in the three parts of the frame: the lower part (floor, luggage compartments), the middle part (sidewalls and window openings) and the roof.

The value of the angular velocity at the moment of impact was determined on the basis of the balance of kinetic and potential energy, according to the formula:

$$\omega = \sqrt{\frac{2 \cdot E_p}{J}},$$

where E_p — the potential bus energy; J — the moment of inertia of the bus relative to the rollover axis located on the upper part of the retaining flange.

The potential energy E_p was determined according to the formula:

$$E_p = M \cdot g \cdot \Delta h,$$

where M — the vehicle mass; g — the gravitational acceleration; Δh — the vertical displacement of the vehicle's CG during rollover test.

When preparing the bus model, the position of the CG was set based on the technical description for the condition of the vehicle. When adding a regulated mass of passengers, the CG position was recalculated.

The Δh value was determined by the geometrical method using the ANSYS software graphic editor. Figure 3 shows a scheme for determining this value:

$$J = J_{OX} + M \cdot r^2,$$

where J_{OX} — the moment of inertia towards the center of mass; M — the mass of the bus; r — the distance from the center of mass of the bus to the rollover axis.

The moment of inertia of the bus towards the center of mass of the J_{OX} was determined using the finite element model of the frame and units using the pre/postprocessor LS-PrePost of the ANSYS LS-DYNA software package. The value of r was determined geometrically in the graphic editor of the ANSYS program.

Based on the obtained values, the angular velocity of the bus was determined at the moment of contact with the impact surface.

Properties of beam structures were set using beam finite elements with the Hughes–Liu formulation taking into account the curvature of open cross sections (variable ELFORM = 1). The shell elements were used with the formulation of Belichko–Tsay (variable ELFORM = 2), as well as in a fully integrated formulation (ELFORM = 16). The number of integration points over the element thickness (NIP) for structures with a low deformation rate was assumed to be 3, for structures with a high deformation rate — 5.

Links between structural elements were defined using contact options *CONTACT_AUTOMATIC_SINGLE_SURFACE and *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE, as well as links directly simulating spot welding — *CONSTRAINED_SPOTWELD.

When preparing models of individual assembly units, verification calculations were performed to assess their performance and adequacy of behavior. A static calculation was carried out to estimate integrity of connections of all elements of the bus superstructure. If there were any loose elements, the load was not distributed on them and they found themselves in a free position. After that, these elements were adjusted and recalculated.

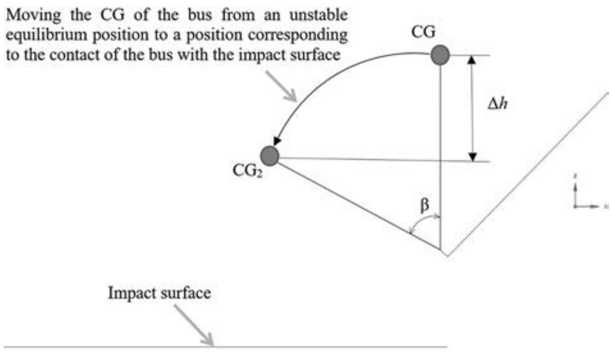


Figure 3 — Calculation scheme for determining the displacement of the CG of the bus

The assembly of the general finite element model of the bus was carried out using the options and settings described above in the preparation of assembly units.

As the models of assembly units were prepared and incorporated into the overall bus model, models of residual space and contact surfaces (impact surface and tilting platform) were added to and guided through the space requirements of the Regulation No. 66. Previously developed contact surface models, which were used in the research of other bus models, can be used. The initial angular velocity of the bus in relation to the rollover axis was set using the *INITIAL_VELOCITY_GENERATION option. In the process of loading, the bus should be subjected not only to the initial kinetic energy, but also to the gravity force, which was set by the LOAD_BODY_Z option.

Setting up the output of calculation results to external files was performed for all types of data, including graphical 3D information (option *DATABASE_BINARY_D3PLOT), change in time of data for model elements and joints (*DATABASE_BINARY_D3THDT), as well as information about change in model energy (*DATABASE_MATSUM) with the same time interval of 1 ms.

After a series of tuning and verification calculations, a model ready for research was obtained taking into account the requirements of the Regulation No. 66. Figure 4 shows the verified model of the bus with contact surfaces in its initial state.

Results of virtual simulation of the bus frame rollover tests for compliance with the requirements of the Regulation No. 66. Comparison with the field experiment. Calculation of the superstructure of the bus during rollover was carried out in accordance with the Regulation No. 66 [1] in the ANSYS LS-DYNA PC finite element analysis software package. The criterion of calculation completion is 95–97 % absorption of kinetic impact energy by the bus structure. Meanwhile the kinetic impact energy corresponds to the potential energy. Further continuation of the calculation is impractical due to the insignificance of the changes and long duration of the calculation. The residual kinetic energy is usually caused by the movement of the bus structure in space and does not affect the deformed state of the superstructure.

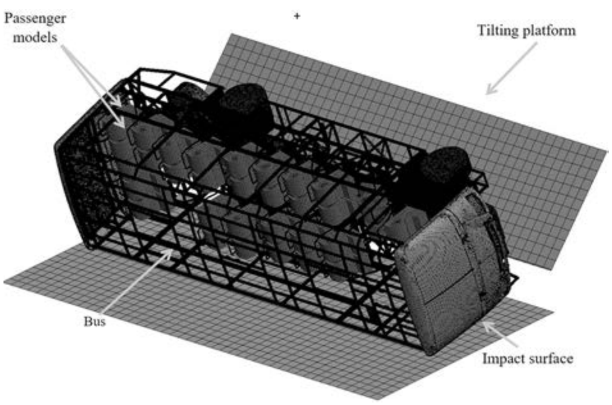


Figure 4 — Computer model for calculating the bus superstructure during passive safety tests during rollover according to the requirements of the Regulation No. 66

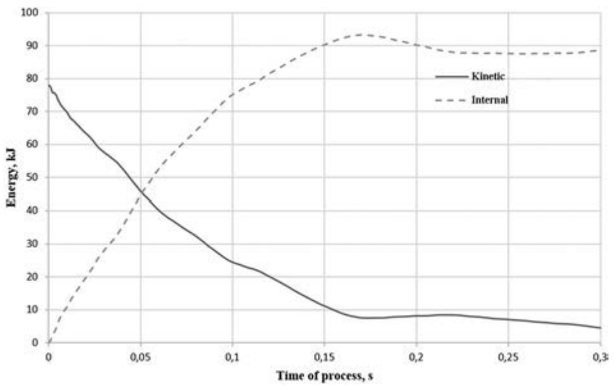


Figure 5 — Dependence diagram of kinetic and internal energy of the bus during the impact surface collision

Figure 5 shows the graph of dependence of kinetic and internal energy of the bus on the time of the process.

The increase in the final internal energy of the bus, compared to the initial kinetic energy, is caused by a larger displacement of the center of mass due to deformation of the frame elements. The kinetic energy losses due to the sliding of the bus frame on the impact surface are taken into account when determining the internal energy.

At Scientific Research Center for the Testing and Improvement of Automotive Technologies (FSUE "NAMI", Russian Federation, Dmitrov) field tests of the bus MAZ 257S30 (a bus for transporting children) were carried out regarding the strength of the superstructure for compliance with the requirements of the Regulation No. 66.

The tests were carried out using the method of tipping over from a ledge in accordance with the method set out in Annex 5 of the Regulation No. 66. The height of the ledge was 800 mm; the vehicle tipped over to the right side; on the driver's and all passenger seats equipped with safety belts, bulk anthropomorphic ballasts with mass of 68 kg each were installed; the axis of rotation of the vehicle during rollover was parallel to the longitudinal axis of the vehicle; the rotational axis was 100 mm from the tire sidewalls of the rear axle; the rotation axis was at a distance of 50 mm vertically from the horizontal reference plane on which the tires rested; the angular velocity of the tilting was 5° per second (0.087 rad/s). Special telescopic rulers were used to measure the dynamic deformations of No. 3 and No. 7 pillars of the body sides.

Figure 6 shows a general view of the bus, including elements of its structure, after field and virtual tests.

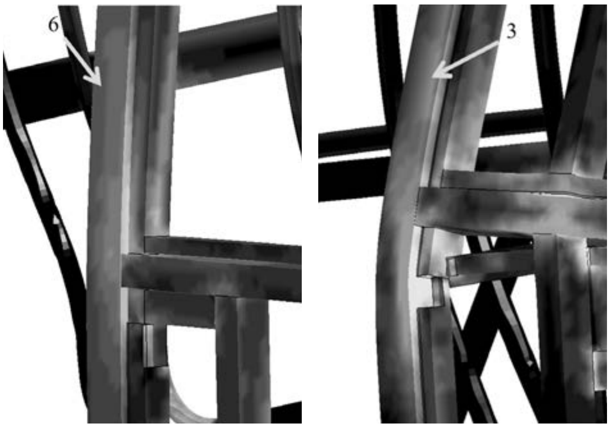
Measurement of movements of the side pillars of the frame was carried out according to the guidelines of the Regulation No. 66, at the highest point of the residual flail space. Figure 7 shows the most deformed elements of the frame.

According to the Regulation No. 66, the maximum permissible dynamic movements of the pillars at the height of the residual flail space relative to the inner wall of the frame, located at the level of the S_R

a

b

Figure 6 — Front view of the deformed bus frame: *a* — field tests; *b* — virtual tests



a *b*

Figure 7 — The most deformed elements of the frame: *a* — pillar No. 6; *b* — pillar No. 3

point, should not exceed 400 mm. According to the results of field tests, the dynamic movements for the pillar No. 3 were 173 mm, for pillar No. 7 were 60 mm. The results of determining the maximum dynamic movements of the frame pillars at the level of the residual flail space height according to the results of virtual tests for the pillar No. 3 were obtained. The result was 195 mm. The inaccuracy in comparison with field tests for the pillar No. 3 was 12.7 %. The estimation of the inaccuracy on the pillar No. 3 was chosen according to the fact that this pillar has the greatest movement and, therefore, limits the properties.

The maximum dynamic movement of the frame pillars is observed at the front. This is due to the initial collision of the bus with the impact surface of the front of the roof.

Conclusion. Computer simulation of the bus superstructure tests for compliance with the requirements of the Regulation No. 66 makes it possible to replace field tests with virtual ones in order to certify products and adequately reflect the behavior of a real structure in case of field tests, taking into account the properties of materials, connections and technological features of structural elements. At the same time, it becomes possible to obtain the VAT of the structure, identify plastic deformation zones in any area and, as a result, improve the superstructure of the bus at the design stage without large material and time costs.

The methodological bases and approaches to carrying out computational researches of the bus model during rollover are developed, based on the transformation of the solid-state geometrical model of the bus superstructure into a shell model, which allows to define the kinematic, dynamic and energy parameters of the rollover. The proposed methodological bases and approaches make it possible to reduce the time required to prepare the model, as the most responsible, time-consuming and knowledge-intensive stage of research. The reduction is achieved by determining the parameters of bus tilting directly in software packages, in which the preparation of the superstructure and the adjustment of the boundary conditions of the model are performed. Some parameters are determined analytically.

The inaccuracy of dynamic movements of the pillar No. 3 according to the results of calculation and full-scale studies was 12.7 %. The magnitude of the inaccuracy is directed to the safety margin of the structure. The value of the inaccuracy is due to the absence in the calculation model of the side trim panels, glasses, door handrails, luggage racks. These elements can be added to the design model. At the same time, the superstructure of the bus meets the requirements without these elements, i.e. the requirements of standards are met with a margin. Additional elements of the body can be taken into account in the bus model if without them the superstructure of the bus does not pass (or at boundary values) tests for compliance with the requirements of the Regulation No. 66. When the superstructure is tested without additional elements, the bus is considered to have a safety margin, and no additional calculations are required.

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ОЦЕНКА СООТВЕТСТВИЯ СИЛОВОЙ СТРУКТУРЫ АВТОБУСОВ ТРЕБОВАНИЯМ ПРАВИЛ ООН № 66 НА ОСНОВЕ КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ ИСПЫТАНИЙ

Рассмотрены существующие подходы отечественных и зарубежных исследователей в области моделирования нагружения каркасов автобусов при расчетной оценке силовой структуры на соответствие требованиям пассивной безопасности при опрокидывании. Определены критерии и основные способы повышения качества компьютерных моделей, сокращения длительности расчетов. Изложены и описаны основы методики выполнения компьютерного моделирования испытаний автобусов на соответствие требованиям Правил ООН № 66 (02)/Пересмотр 1. «Единообразные предписания, касающиеся официального утверждения крупногабаритных пассажирских транспортных средств в отношении прочности их силовой структуры» (далее — Правила ООН № 66). Приведен пример компьютерного моделирова-

ния испытаний силовой структуры пригородного автобуса при опрокидывании с помощью программного комплекса конечно-элементного анализа ANSYS LS-DYNA. Подготовка модели выполнена в программе LS-PrePost.

Ключевые слова: *силовая структура, автобус, пассивная безопасность, компьютерная модель, конечно-элементный анализ, угол опрокидывания, опрокидывающая платформа, момент инерции, начальная угловая скорость, потенциальная энергия удара, Правила ООН № 66*

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