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Original scientific paper

Verification of the Numerical Model of Optimized Bus Body Structure According to UN Regulation No. 66

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Abstract: Bus rollover is one of the most analyzed cases of accidents, having in mind the number of potential large number of injuries and fatalities. Therefore, this type of traffic accident became the object of numerous national and international standards and regulations. The aim of this paper is to investigate the possibilities of experimental verification of presented simplified model of the bus body section. For that purpose, completely new multifunctional test bench was presented. The methodology applied for the experimental part was explained. The results provided by the numerical simulation and by the experiment were presented, and appropriate analyses were performed. The key parameters needed for the experimental verification were specified. According to the result analysis, a comparative results review was presented, confirming that the experimental verification of the numerical model was fully acceptable. Also, all of the requirements prescribed by the applied methodology for the achieved results acceptance were fulfilled, providing that numerical simulation, with constant improvements, could be a powerful tool for quick and reliable bus structure analysis in design process.

Keywords: numerical simulation; redirected design; rollover; UN Regulation No. 66; verification

1 INTRODUCTION

Bus manufacturers worldwide put a lot of attention to problems related to passive safety, since buses were recognized as road vehicles intended for a large number of passengers to be transported at the same time. Therefore, rollover is maybe not the most common, but definitely the most severe and most analysed type of traffic accidents involving busses.

At the same time, bus rollover is the object of international and national standards and regulations for a long time. The strength of bus body structure became the topic of UN Regulation No. 66 in December 1986 [1]. According to the Regulation, certain body structure strength and appropriate level of energy that structure should absorb was required, providing that passenger residual space stays unreachable by any displaced part of the structure.

Ever since, this UN regulation has been constantly updated and changed, following the requirements of increased passive safety. The latest changes of UN Regulation No. 66, provided through the 02 Series of amendments [2], stated a much wider group of bus classes to undergo tests prescribed within this UN Regulation. These changes became even more important, having in mind that smaller busses, mainly classified as Class B, make a significant part of public transportation nowadays.

On the other hand, most Class B busses were produced through the modification of originally made N2 category vehicles, and if there are no changes in the bus structure, they are covered with R66 Approval of the base vehicle. Requirements related to passenger comfort and advanced design demands very often have to be followed with some structural changes, especially in higher zones of the bus construction, providing larger glass surfaces. Therefore, the Approval of the base vehicle regarding bus body strength is no longer valid, so a completely new testing procedure has to be conducted to the modified structure. Therefore, a quick numerical analysis could be very important in this process, because prescribed physical tests take too much time and require a lot of investment to prepare the structure.

Within this paper, a numerical model prepared for the analysis was presented, as well as the software used for it. Also, in order for the model to be verified, a completely new multifunctional test bench was introduced, explaining the improvements in the testing procedure. Finally, achieved results were presented, with appropriate analysis and conclusions regarding the process of verification of numerical models.

This process related to UN Regulation No. 66 was subjected to the analysis of numerous articles for many years. Early papers [3] to [5] dealt with simple simulation software solutions. More recent articles [6] to [9] analysed numerical verification that used up-to-date FEM simulation tools, with more reliable comparative analyses. Also, paper [10] proposed an improved criterion for supervision of the crashworthiness. On the other hand, some authors analyzed the behaviour of bus body structure made of composite material [11]. Furthermore, paper [12] proposed changes in regulation, by placing higher requirements for the structure. Recent papers [13] to [15] deal with formation of motion cueing algorithm for motion simulation platform based on model predictive control, for achieving better motion feeling compared with the current models.

The main goal of this paper is to present a numerical model good enough for an accurate analysis process and simple enough to be quickly modified in order to get an optimized structure. Also, for the verification of the achieved numerical model, the main task is not to use the rollover test of the complete body structure (although it is the most reliable method), but to use the quasi-static loading test of the body sections of the structure. Such an approach enables us to follow the behaviour of the body structure throughout the complete physical test and to notice all potential weak points. With rollover test of the complete body there is just a final result, with no possibilities to examine the main characteristics of the structure and to initiate weak points.

Therefore, the objective of this paper is to provide the simplest possible numerical model which would allow quick changes upon the information acquired by the physical tests, and analysed through the method of redirected design [16]. With such an approach, we can make quick changes and achieve an optimized numerical model, verified by the prescribed method, with less time and less costs.

2 NUMERICAL MODEL

The geometry used to make a numerical model of the middle section of the bus structure is shown in Fig. 1. It is a full-scale model representing a real middle section consisting of 74 steel beams with 4 different cross-sections. The steel used in simulations has a yield strength of 250 Mpa and tensile strength of 440 MPa, with a tangent modulus of 1,450 MPa (used to describe bilinear isotropic hardening) obtained experimentally. Thus, the nonlinear properties of the material were considered.

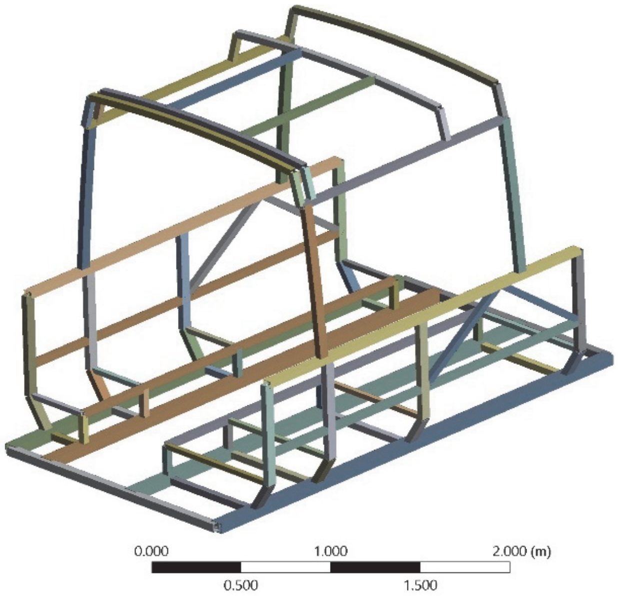

Figure 1 Geometry of the middle section structure

Four bottom beams (shown in blue color in Fig. 2) were fixed during numerical simulations, while the force of 18,000 N was applied on five beams shown in red in Fig. 3.

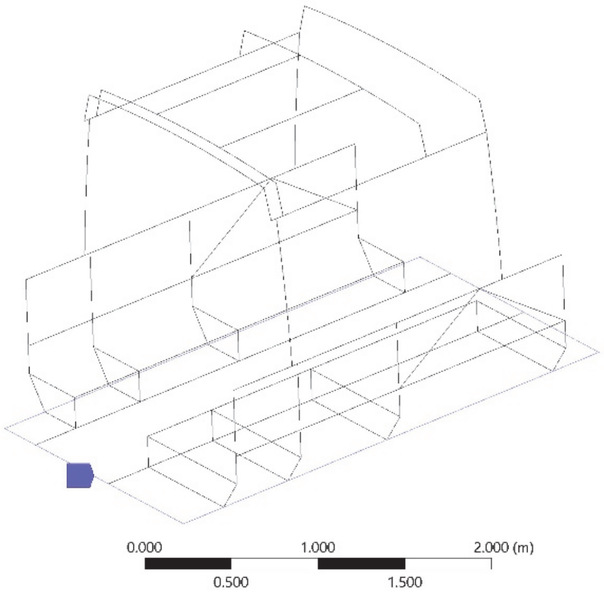

Figure 2 Fixed bottom beams

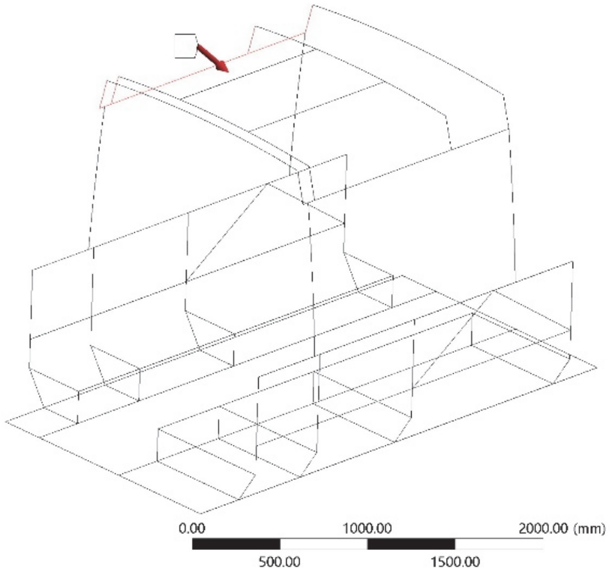

Figure 3 Direction of applied force

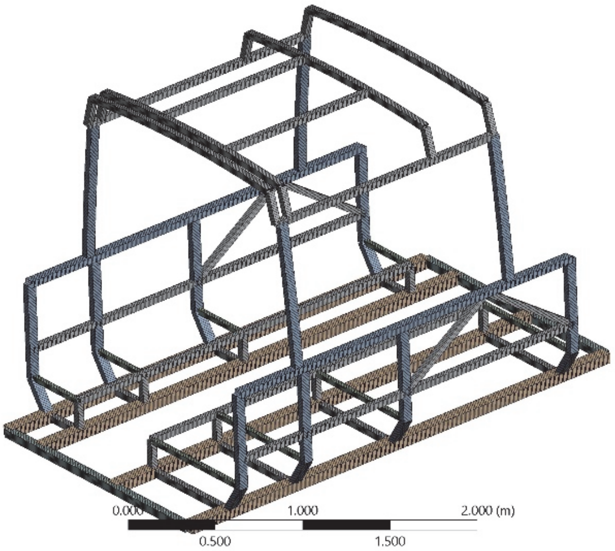

Figure 4 Finite element mesh used in numerical analysis

Finite element mesh (shown in Fig. 4) created in Ansys Workbench consisted of 13,538 nodes and 6,764 elements of type BEAM188. The average size of an element was 10 mm and in total 158 bonded contacts between elements have been created using CONTA177 elements.

3 EXPERIMENTAL VERIFICATIONS

In order to verify the numerical model, one of the physical tests provided by UN Regulation No. 66 has to be chosen. Like previously mentioned, a quasi-static loading test of body sections of the structure was selected, since the behaviour of the body structure can be followed all the time of testing. Notification of potential weak points of the structure could be very important feedback for the numerical model, in a way to be improved if needed.

3.1 Test Bench

For the purpose of conducting the selected test method, a newly designed multifunctional test bench was introduced (Fig. 5).

Figure 5 Test bench for physical tests according to UN Regulation No. 66

Multifunctionality of the test bench was reflected through the implementation of all physical tests provided by the UN Regulation:

- Rollover test of the complete body structure;
- Rollover test of body sections;
- Quasi-static loading test of body sections.

The test bench consists of two strong longitudinal members, firmly connected to each other with transversal supports, forming a base platform for all of the provided tests. For the quasi-static loading test, the base platform was used for positioning and fixing the tested body section, as well as for fixing of support of beam and hydraulic cylinder for applying the load. The inclination of applied load was determined depending on the cantrail height and easily adjusted by the position of the tested body section.

For both rollover tests, the base platform was raised to the height prescribed for starting height of a rollover test. Beam and its support are removed from the platform, and hydraulic cylinder needs to be displaced under the base platform, providing its tilting and rollover of tested samples. All these modifications of the test bench could be carried out in a reasonable short time, providing the adjustment of the testing equipment to the desires of the customers.

3.2 Test Samples

Test samples for the quasi-static loading test should be selected in a way to clearly represent the complete bus body structure. Since the body structure of the modified N2 category vehicle was used, there were no repetitive segments, so the whole body structure was divided into three sections: front, middle and rear.

Each of these three segments has its own properties since the construction of the segments is completely different. The front segment consists of a front panel and one vertical pillar, as a part of the characteristic ring of the structure. The middle segment consists of two vertical pillars, both as a part of the characteristic rings of the structure. Finally, the rear segment consists of one vertical pillar, as a part of the characteristic ring of the structure and complete rear panel.

In such a case, the easiest way is to prepare the complete body structure for testing (as one piece), and to divide it by cutting vertically downward to the zone where the testing of one of the body sections has no influence to the others. Complete body structure divided into sections and prepared for testing is shown in Fig. 6.

Figure 6 Body structure divided into three sections for the purpose of quasi-static loading test

Order of body sections testing by quasi-static loading test was not defined by the UN Regulation. Therefore, tests could be performed randomly, by the choice of producer or Technical Service.

4 RESULTS

For the purpose of numerical model verification, the results of the numerical model and quasi-static loading test of the middle section were presented through diagrams and comparative tables. As an outcome from the numerical model, force, deformation and energy absorption were shown, while from the quasi-static loading, force and deformation were measured, and energy was calculated upon measured quantities.

Since force applied should cause plastic deformation of the analyzed structure, force convergence was observed, and - as can be seen in Fig. 7 - simulation successfully converged after 292 cumulative iterations.

Fig. 8 shows the total deformation (displacement) of the numerical model obtained in FE simulation, while Fig. 9 shows stress distribution in the model.

It is observable that stress obtained in numerical simulation exceeds the yield strength of the material (250 MPa) in several beams, with the maximum value of 426 MPa obtained in one node only (indicated by tag *Max* in Fig. 9). This value is very close to the tensile strength of the material used (440 MPa), but there was no indication of beam failure at that position in the experiment. Analysis of stress values in nodes that surround the node with maximum stress showed that 426 MPa was singularity (caused by defined boundary conditions at that node) since all neighbor nodes had stress values at least 20% smaller than the maximum calculated stress. However, Fig. 9 shows a dozen beams with combined stress higher than 280 MPa (yellow and orange color) where plastic deformation occurs in simulation. Plastic deformation occurred in experiments in the same beams, which was the evidence that the FE model was well defined. Thus, these beams can be considered critical or weak parts of the structure that should raise the attention of engineers in the future.

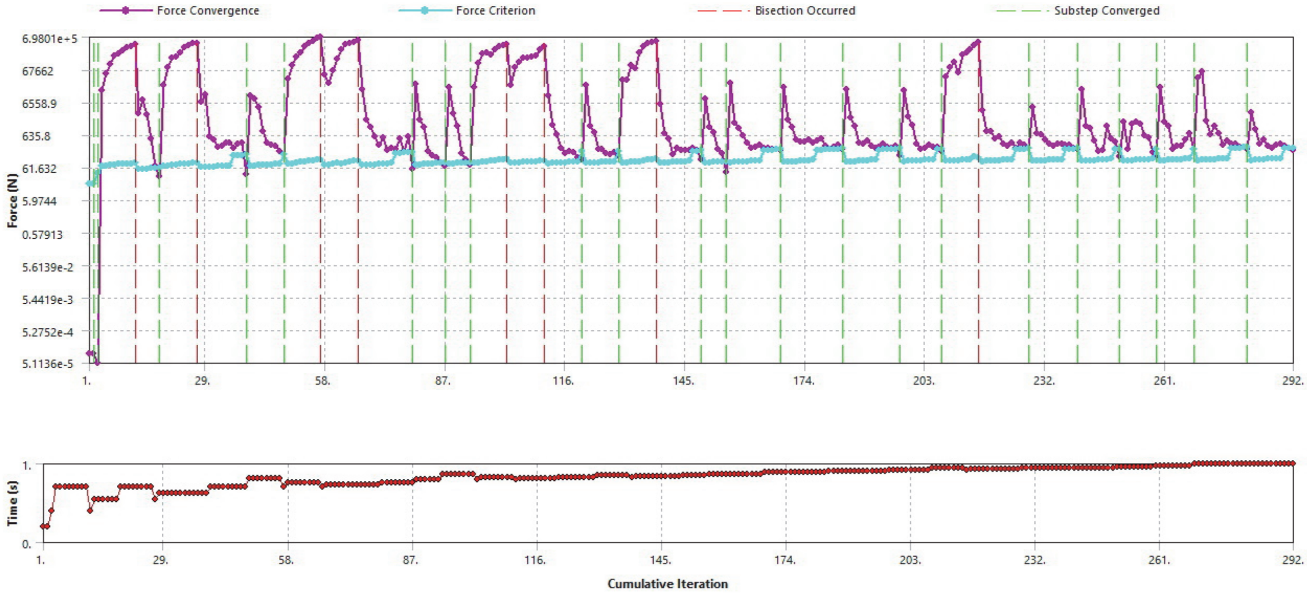

Figure 7 Force convergence achieved

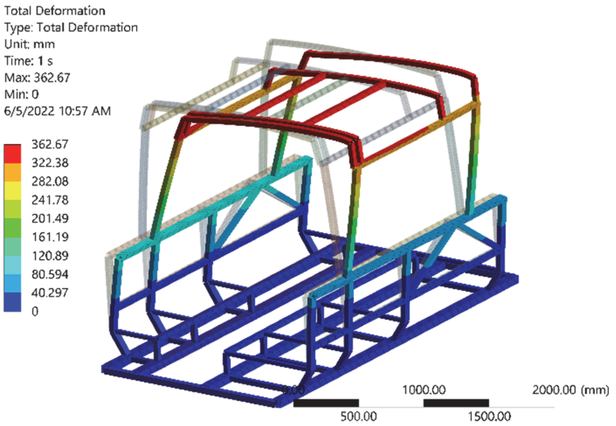

Figure 8 Maximum deformation of upper beam (363 mm)

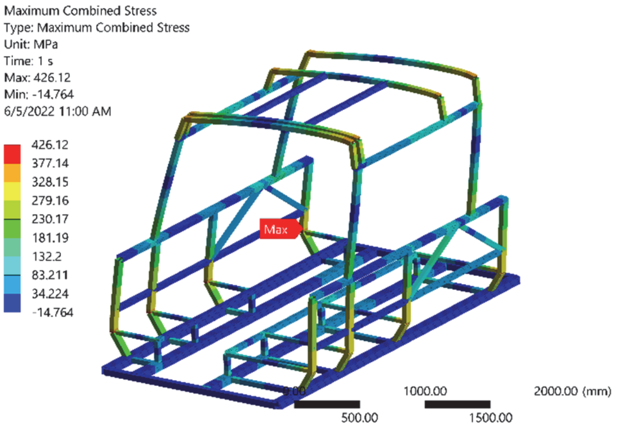

Figure 9 Stress distribution with maximum value of 426 MPa

The graph in Fig. 10 shows the change of energy with the deformation of the structure. Later this value of energy will be compared to energy measured in the experiment for the purpose of numerical values verification.

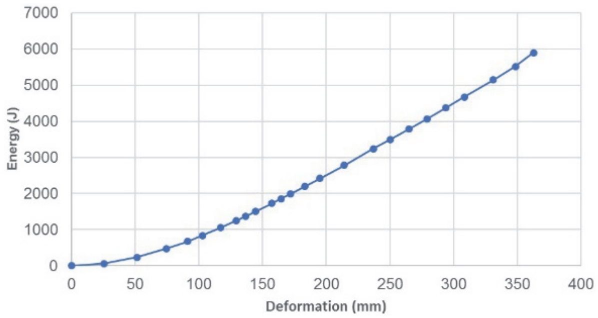

Figure 10 Energy - Deformation diagram for numerical model

The results of the quasi-static loading test of the middle section are shown in Figs. 11 to 13. Fig. 11 shows the value ratio of force and deformation achieved by the experiment. Certain decreases of implemented force were noticed, since the body section entered into the zone of plastic deformations.

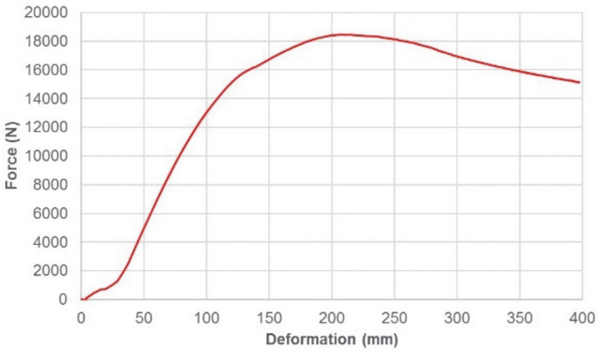

Figure 11 Force - Deformation diagram from the experiment

Fig. 12 shows the value ratio of absorbed energy and deformation achieved by the experiment. These values were considered to be the main items for the comparative analysis needed for the verification if the created optimized numerical model could be accepted as valid.

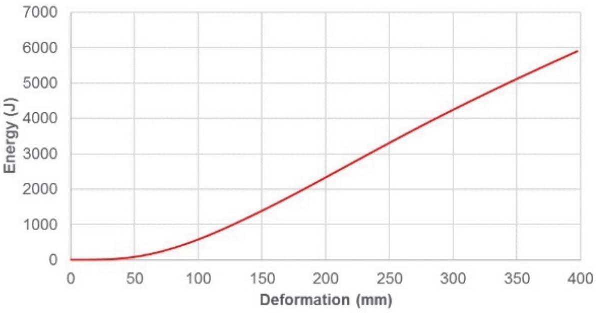

Figure 12 Energy - Deformation diagram from the experiment

Fig. 13 shows the increase of calculated absorbed energy value in time. It was noticed that at the beginning of the test energy values were very low, mainly as a result of the pace of force increase and the rigidity of the bus body section structure, which is reflected in low deformation values.

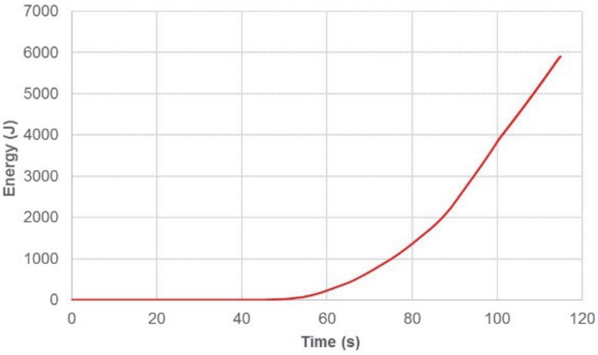

Figure 13 Energy-in-Time diagram from the experiment

For the final verification of the numerical model, comparative values of force and deformation obtained through numerical simulation and quasi-static loading test were summarized in Tab. 1.

Table 1 Middle section comparative results

	Numerical simulation	Physical test	Difference / %
Applied force / kN	18,0	18,4	2,22%
Deformation / mm	363	397	9,37%
Level of energy / kJ	5,90	5,90	-

The results were compared for the desired level of absorbed energy (5,9 kJ), appointed as acceptable for the middle section of the bus body structure.

Fig. 14 shows a comparative view of energy and deformation values achieved by numerical analysis (blue line) and by experiment (red line).

The differences of deformation achieved by numerical simulation and by experiment in the middle energy zone (most of the energy range) are less or about 5%, while in the lower energy zone the difference is higher, and in the upper energy zone the energy grows to about 9,4%.

The deformation differences in the lower energy zone occur due to the clearance in the construction and measuring equipment settings, so the deformations achieved by the experiment are much higher (increase in deformation without an increase in force, so there is no energy) than the deformations achieved by the numerical analysis. However, that part of the diagram is not important and crucial for the final results and verification of the model, so that differences were not taken into consideration.

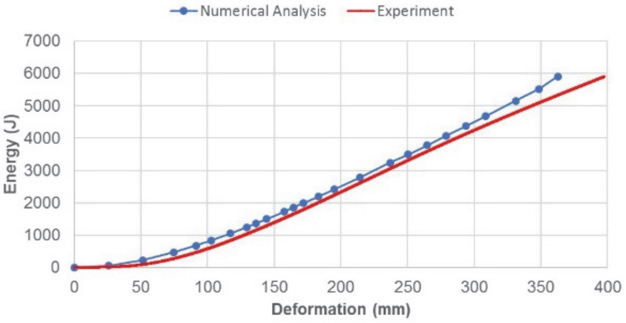

Figure 14 Comparative Force - Deformation diagram (Numerical analysis and experiment)

As for the upper zones, the deformation differences can be explained by the behavior of the material in the plastic zone. This can be seen in Fig. 9, where the decrease of force was noticed after entering the zone of plastic deformation and the deformation continues to increase, which results in increased deformation difference. At the same time, numerical simulation at this level does not recognize the negative gradient of force in the zone of plastic deformation, so the simulation was performed with the constant force after reaching the maximum value.

5 CONCLUSIONS

For the declared energy level of the middle section of the bus body structure (5,9 kJ), the maximum achieved difference of deformation is less than 9,4%, so the results could be considered acceptable for the numerical simulation verification. At the same time, the values of deformations achieved by the experiment and by the simulation are in the zone away from the maximum expected deformation for residual space violation (450 mm).

According to the required conditions for the acceptance of the results, both requirements were fulfilled: the expected level of energy was achieved, and the residual space remained unviolated.

Future activities should be focused on the research of the influence of variable force on the results (energy and deformation), now by taking force values from experiment and by introducing them into numerical calculations for further model improvement. This approach is completely in accordance with the method of redirected design, providing the reduction of time and costs in the structure design phase.

On the other hand, the results of such analysis should bring us to the activities focused on optimal structure design and achieving the total mass reduction. Of course, these activities have to be followed with more detailed analysis of the characteristics of joints, considering the possibilities of their strengthening.

Moreover, the usage of such an optimized numerical model does not have to be limited only to mid-sized busses, it could be applied to any bus body structure, no matter of its size and complexity.

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