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THE APPLICATION OF COMPUTER SIMULATIONS AT THE AMERICAN BUS DESIGN

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Summary: *ŠKODA VÝZKUM s.r.o. cooperated at the development of the NEOPLAN RQ low-floor bus intended for the Boston city (the United States). Multibody models and finite element models of the bus were utilized in the stage of the bus design. The multibody models of the bus were created in the* ***alaska*** *simulation tool and the simulations of running over the large road unevenness represented by the artificial obstacles were aimed at determining forces acting in the bus suspension elements. Time histories of the forces calculated using multibody models were used as the input data of the bus finite element models. Utilizing the finite element models created in the COSMOS/M software the critical places of the bus body structure from the point of view of high stresses were determined. At the measurement with the real bus prototype these places were equipped with strain gauges.*

1. Introduction

Optimum dynamic properties of a vehicle intended for public transport can usually be achieved in dependence on its structural design by the proper choice of the axles' suspension elements. The design must be the compromise of the requirements for the vehicle behaviour during driving manoeuvres, for the riding comfort and for the vehicle body and the chassis parts lifetime when driving on an uneven road surface, and for the passenger safety (e.g. Genta & Morello, 2009).

Driving on the uneven road surface can reveal many facts about the vehicle vertical dynamic properties and about the suitability of the used suspension elements of axles. Especially time histories of relative deflections of springs, relative velocities in the shock absorbers, stress acting in the axles' radius rods or radius arms and acceleration in various points in the vehicle interior are the monitored quantities (Gillespie & Karamihas, 2000). On the basis of relative deflections of springs, relative velocities in shock absorbers and stress acting in radius rods or radius arms it is possible to determine the time histories and the extreme values of the forces acting in the suspension elements of axles which can be utilized in connection with the suitable computational methods for the stress analysis of structures, for the prediction of the fatigue life of the body and the chassis parts of the tested vehicle (e.g. Vlk, 2000).

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In 2003 Neoplan USA Corporation, the American producer of buses and trolleybuses started to develop the NEOPLAN RQ low-floor bus intended for the Boston city (see Fig. 1). ŠKODA VÝZKUM s.r.o. cooperated at the development of the bus. The multibody models and the finite element (FE) models of the bus were utilized in the stage of the bus design. The multibody models of the bus (empty and fully loaded) were created in the **alaska** simulation tool (Maißer et al., 1998) and the simulations of running over the large road unevenness represented by the artificial obstacle were aimed at determining forces acting in the bus suspension elements (Polach, 2004). Time histories of the forces calculated using multibody models were the input data of the bus FE models. Utilizing the bus FE models (empty and fully loaded, too) created in the COSMOS/M software (SRAC, 1999) the critical places of the bus body structure from the point of view of high stresses were determined (Jankovec, Smola & Hejman, 2004). At the measurement with the real bus prototype these places were equipped with strain gauges. The measurement with the real trolleybus was also performed by ŠKODA VÝZKUM s.r.o., but it is not a topic of this paper.

Fig. 1: The NEOPLAN RQ bus (in the assembly hall).

2. Bus multibody models

The multibody models of the NEOPLAN RQ bus are formed by 25 rigid bodies mutually coupled by 31 kinematic joints. The number of degrees of freedom of multibody models in kinematic joints is 95. The rigid bodies correspond to the bus individual structural parts and one "auxiliary" body, which is used due to limited possibility of choice of kinematic joint types in the **alaska 2.3** software (generally, proper introducing the "auxiliary" bodies into multibody models enables to reduce the number of equations solved in the course of simulating operational situations) are concerned. Rigid bodies are defined by inertia properties (mass, centre of gravity coordinates and mass moments of inertia). Air springs and hydraulic shock absorbers in axles' suspension and bushings in the places of mounting certain bus structural parts are modelled by connecting the corresponding bodies by nonlinear spring-damper elements. When simulating driving on an uneven road surface the contact point model of tires is used in the multibody models; radial stiffness and radial damping properties of tires are modelled by linear spring-damper elements considering the possibility of bounce of the tire from the road surface (Kovanda, Resl & Socha, 1997).

The body of the NEOPLAN RQ bus is virtually divided into the front and the rear parts in the multibody models (see Fig. 3) due to the more precise approximation of dynamic behaviour of the vehicle. These parts are connected by a spherical kinematic joint. Using appropriately chosen torsional stiffnesses in the kinematic joint, this model of the bus body enables to "tune" the values of natural frequencies corresponding to their first bending vibration modes (vertical and lateral) and to their first torsional vibration mode to the natural frequencies of the FE model of the bus body (Jankovec, Smola & Hejman, 2004) created in the COSMOS/M software.

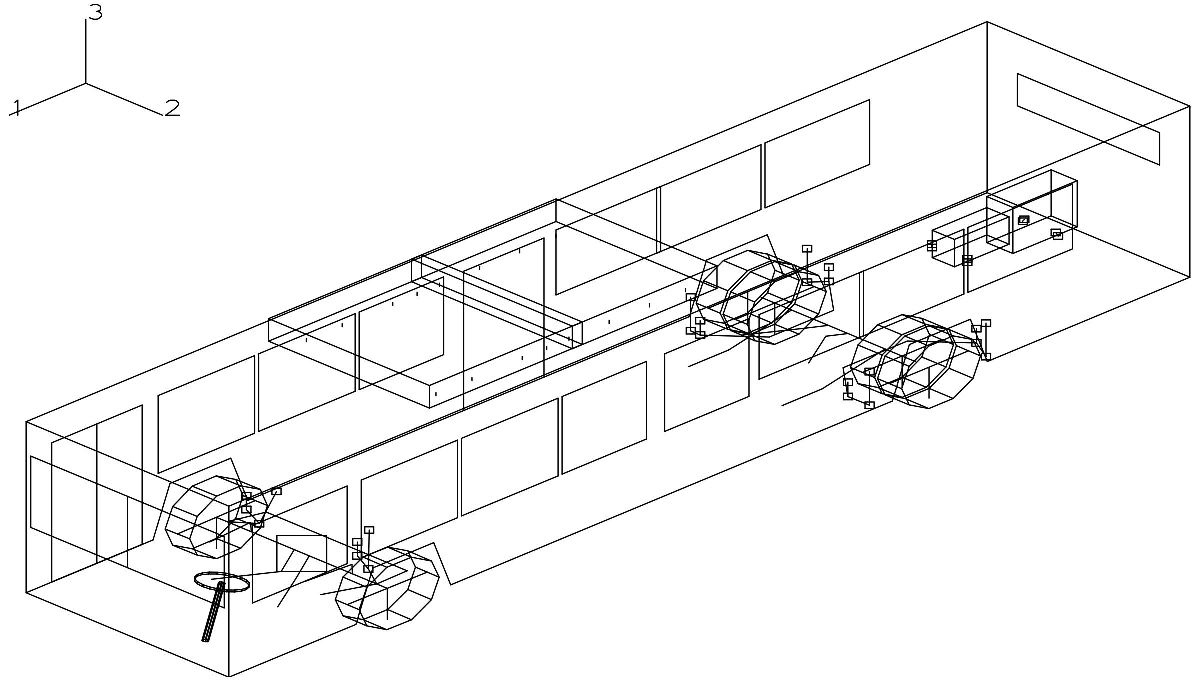

Fig. 2: Visualization of the multibody model of the NEOPLAN RQ bus.

Multibody models of the NEOPLAN RQ bus are created especially on the basis of data (numerical data and technical documentation) provided by NEOPLAN USA Corporation (Polach, 2004). Certain input data were derived or taken from the data used in the multibody models of the ŠKODA 22 Ab low-floor articulated bus (Polach, 1999), certain ones were determined using in-house computing programs (created in Microsoft FORTRAN programming language – Microsoft, 1989), certain data about the bus body were acquired from the bus FE models (Jankovec, Smola & Hejman, 2004) created in the COSMOS/M software. Characteristics of axles air springs are determined on the basis of static loadings of axles derived from data provided by the producer of springs (the Firestone company) using the Microsoft Excel spreadsheet. Characteristics of shock absorbers in axles' suspension were the part of the documentation provided by NEOPLAN USA Corporation. Stiffness data of the bushings in the assembly eyes for connecting radius rods to axles and chassis frame are taken from the documentation of the Lemförder Metallwaren and the Autófelszerelési Vállalat Sopron companies. When choosing damping coefficients of bushings in the assembly eyes of the axles' radius rods pieces of knowledge were taken from the simulations with the multibody models of the ŠKODA 22 Tr low-floor articulated trolleybus (Polach, 2002).

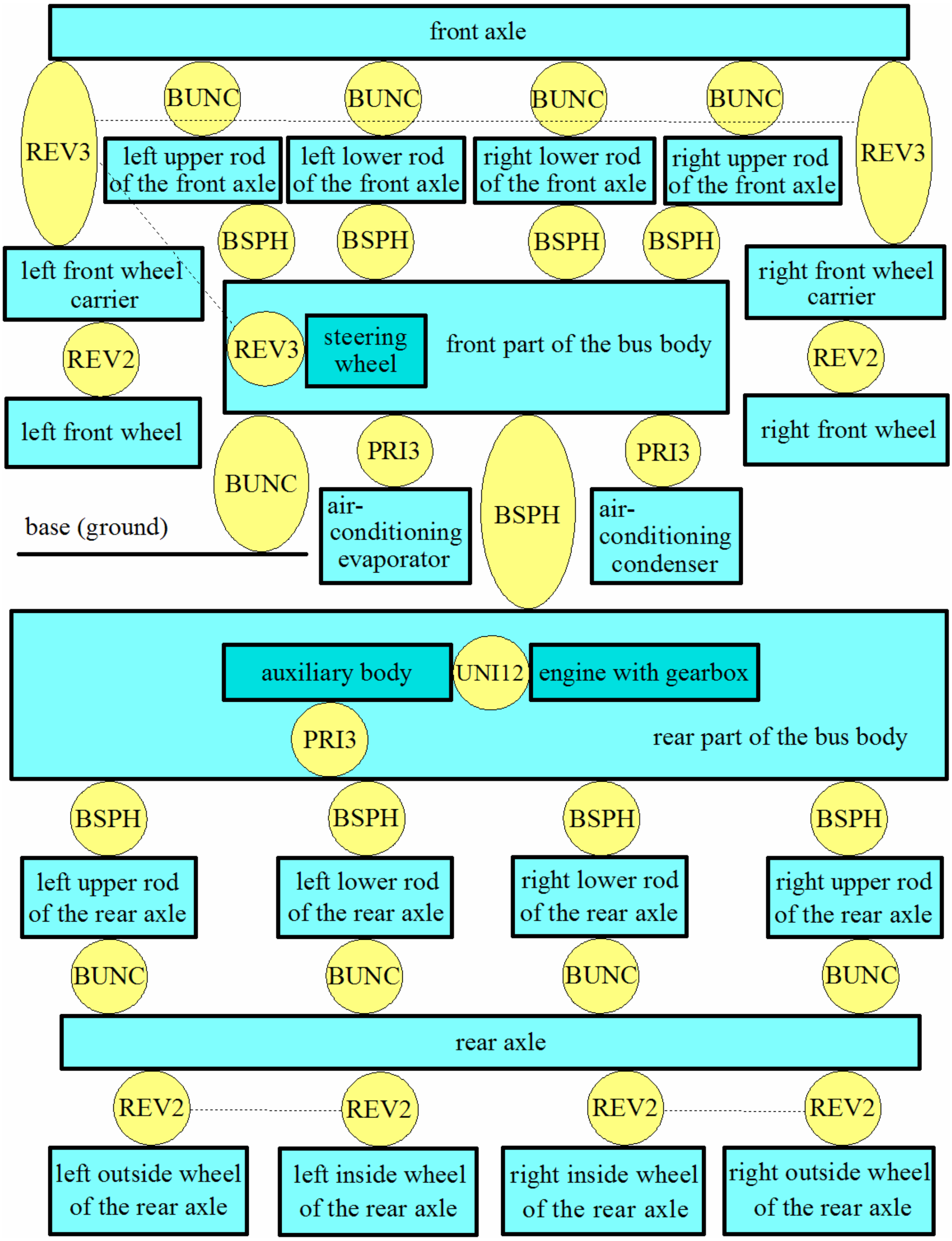

Fig. 3: Kinematic scheme of the bus multibody models.

For illustration, total mass of multibody model of the empty NEOPLAN RQ low-floor bus (Boston version) is 14 179.16 kg, mass of multibody model of the fully loaded bus is 19 577.16 kg.

Generally, the aim of the simulations with the multibody models of the NEOPLAN RQ low-floor bus is the determination of time histories or FFT results of time histories of monitored kinematic and dynamic quantities in the course of the chosen operational situation.

Kinematic scheme of the NEOPLAN RQ bus multibody models is in Fig. 3. Rectangles designate the rigid bodies, circles (or ellipses) designate the kinematic joints (BUNC – unconstrained, BSPH – spherical, UNI12 – universal around axes "1" and "2", PRI3 – prismatic in axis "3" direction, REV2 – revolute around axis "2", REV3 – revolute around axis "3"; axes of the coordinate system are considered according to Fig. 2). Dashed lines connect mutually dependent kinematic joints.

3. Simulations of running over the road unevennesses

Simulations of running over the large road unevenness represented by the artificial obstacle of the height 60 mm (according to the Czech Standard ČSN 30 0560 Obstacle II – see Fig. 4) were performed with multibody models of both the empty and the fully loaded bus at driving speeds 40 km/h. Running over the obstacle with all the wheels, the right ones and the left ones were simulated.

Vertical coordinates of the standardized artificial obstacle $z(x)$ are given by the formula

$$z(x)=\sqrt{R^2-\left(x-\frac{d}{2}\right)^2}-(R-h)\quad , \qquad (1)$$

where R (= 551 mm) is the obstacle radius, h (= 60 mm) is the obstacle height, d (= 500 mm) is the obstacle length and x is the obstacle coordinate in the vehicle driving direction.

Considering the previously performed numerical experiments (Holeček & Polach, 1998) and experience, the shape of the artificial obstacle for the simulations with vehicles multibody models at the contact point tire model utilization was modelled by means of the so called "*hat" profile* function:

$$\text{"}hat\text{"}\ profile = \begin{cases} h_0 & \text{, if } x \le x_0 \\ h_0+\frac{z}{2}\cdot\left[1-\cos\left(2\cdot\pi\cdot\frac{x-x_0}{x_1-x_0}-\frac{\pi}{2}\right)\right] & \text{, if } x_0 < x < x_1 \\ h_0 & \text{, if } x_1 \le x \end{cases} \qquad (2)$$

where x is the longitudinal coordinate, z is the vertical coordinate, h_0 is the constant (in case of the obstacle the road height, i.e., $h_0 = 0$), x_0 and x_1 are coordinates of the beginning and the end of the obstacle. Comparison of the real standardized obstacle shape with its approximation by means of the "*hat" profile* function according to equation (2) is in Fig. 4.

When simulating movement with the multibody models, nonlinear equations of motion, which are solved by means of numerical time integration, are generated. Results of the simulations were obtained using the Shampine-Gordon integration algorithm (Maißer et al., 1998).

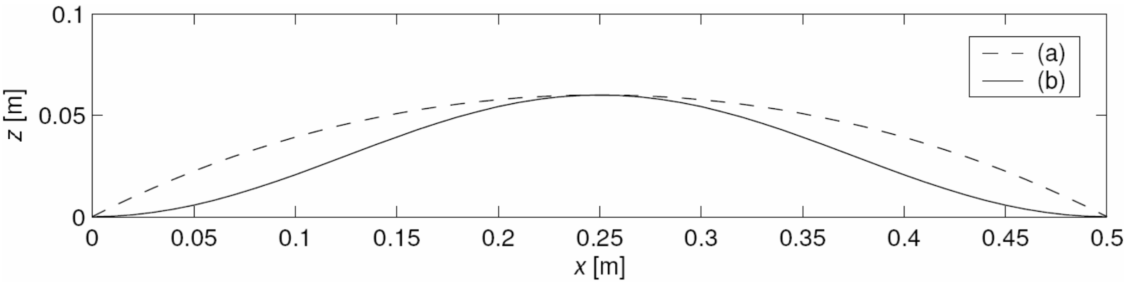

Fig. 4: Real shape of the artificial standardized obstacle (a) and its approximation by the *"hat" profile* function (b).

Approximately constant speed of bus multibody models is assured by the acting of the driving torque on the wheels of rear driving axle when simulating running over the large road unevenness. When the bus speed decreases below the required value of the speed continuous driving torque acts in driving direction, when the required speed is re-achieved it equals zero.

All the considered runnings over the artificial standardized obstacle start 4 seconds after the beginning of the bus multibody models driving simulation. This time is sufficient for dynamic processes fading away in multibody model transition from the starting position (it is not identical with the equilibrium position, it is given by the initial setting of the kinematic joints in the multibody models) to the steady state before the beginning of the operational situation simulation.

Forces acting in axles' suspension elements (i.e. in air springs and shock absorbers) and axial forces acting in axles' radius rods were the monitored quantities. Simulations results are used (together with time histories of directions of axles' radius rods considering the bus chassis frame) as input data for the calculations of the stresses of FE models of the bus body (Jankovec, Smola & Hejman, 2004) in the COSMOS/M software.

Time histories of dynamic forces acting in the front air spring and time histories of forces acting in front shock absorbers are given in Fig. 5 for the illustration. Time histories of axial forces acting in the front and in the rear axles' radius rods are given in Fig. 6. The time histories in Figs 5 and 6 (time is in seconds, forces are in Newtons) were obtained at the simulations with the empty bus multibody model and the obstacle was run over with the right wheels.

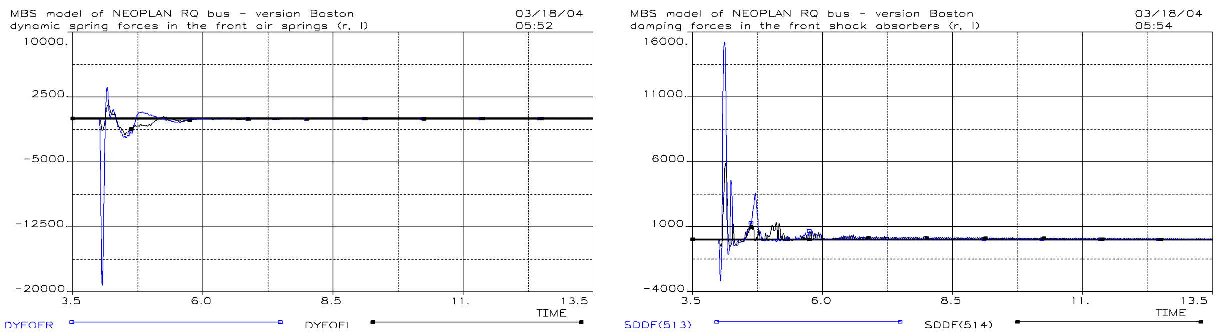

Fig. 5: Time histories of dynamic forces acting in the front air springs (DYFOFR – right spring, DYFOFL – left spring) and time histories of forces acting in the front shock absorbers (SDDF(513) – right shock absorber, SDDF(514) – left shock absorber); empty bus; running over the obstacle with the right wheels.

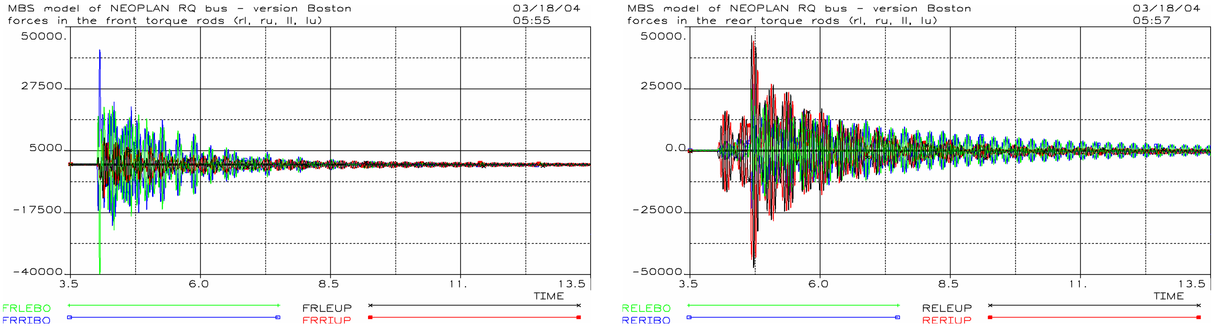

Fig. 6: Time histories of axial forces acting in the front radius rods (FRLEBO – left lower rod, FRRIBO – right lower rod, FRLEUP – left upper rod, FRRIUP – right upper rod) and in the rear radius rods (RELEBO – left lower rod, RERIBO – right lower rod, RELEUP – left upper rod, RERIUP – right upper rod); empty bus; running over the obstacle with the right wheels.

4. Bus finite element models

The COSMOS/M commercial software (SRAC, 1999) was used for the finite element (FE) simulations with the bus body (Jankovec, Smola & Hejman, 2004). The pre- and post-processing Geostar module was used for the model creation and for the evaluation of the results. The linear static analysis was solved using the STAR module and the dynamic analysis was solved using the DSTAR module.

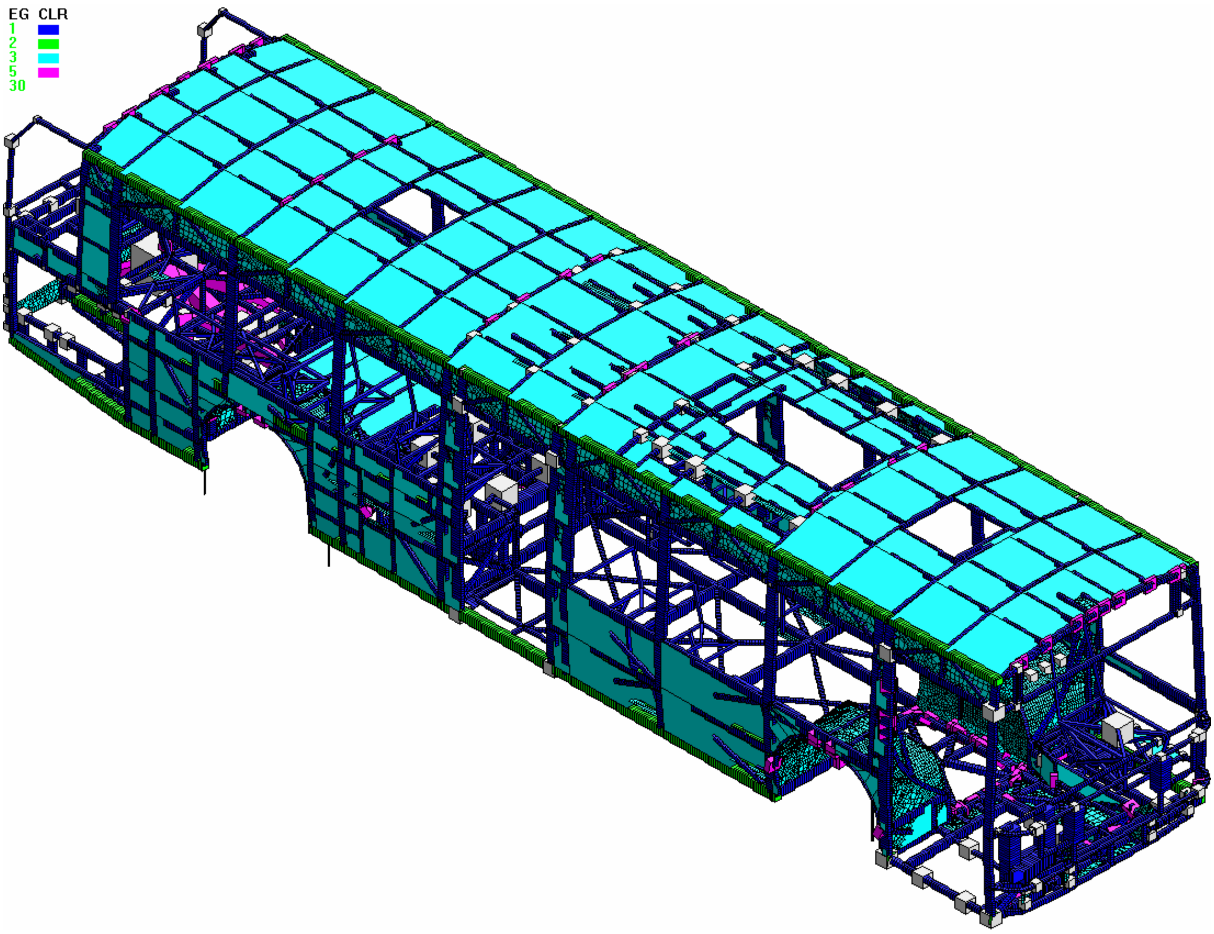

Fig. 7: The FE model of the NEOPLAN RQ bus.

The following four load cases were computed:

- static (a load case corresponding to 1g vertical acceleration),
- driving over the obstacle with both wheels,
- driving over the obstacle with left wheels,
- driving over the obstacle with right wheels.

Each load case was simulated for two bus configurations:

- an empty bus,
- a fully loaded bus (loaded by passengers).

The linear static analysis was used to investigate the bus structure under the gravity loading. The dynamic analysis was used to investigate the structure at the bus driving on an uneven road surface.

The FE models of the NEOPLAN RQ bus (see Fig. 7) were created on the basis of the design documentation provided by the bus producer Neoplan USA Corporation. The bus is modelled using several finite element types from the COSMOS/M software element library. The frame, sidewalls, roof, front wall and rear wall of the bus structure are modelled using the BEAM3D elements. The size of the beam elements is 25 milimeters; both symmetric and unsymmetrical beams were used. Skin on the sidewalls and on the roof is modelled using the SHELL4 (thin-walled shell) elements. The RBAR (rigid bar) elements were used for the connection of a certain beam and shell elements. The MASS elements represent additional masses connected to the bus body structure. This element type was also used for the masses modelling the distribution of passengers in the bus interior.

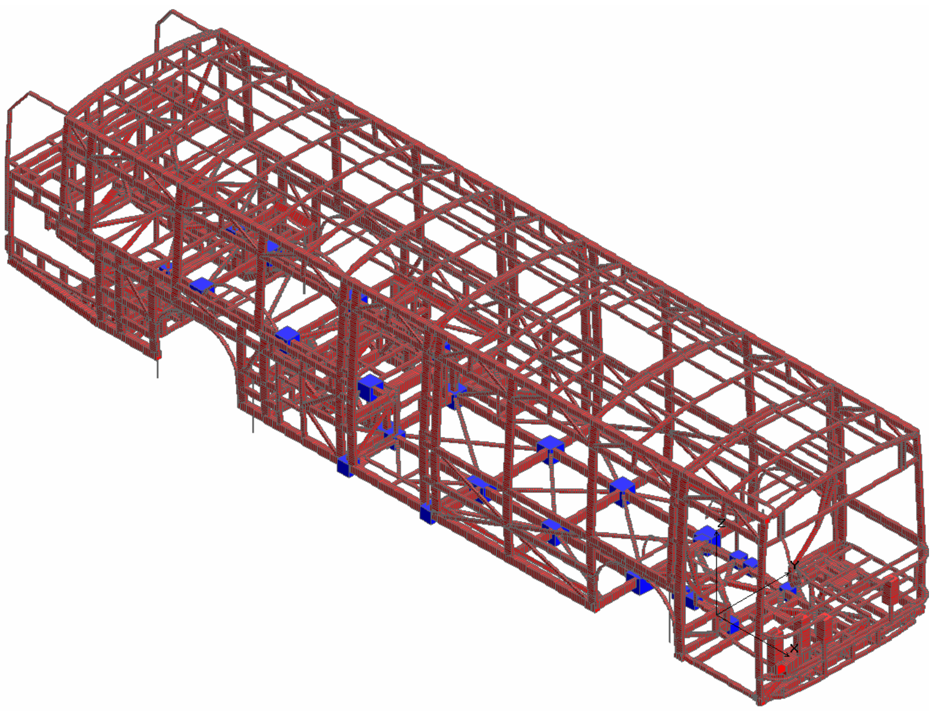

Fig. 8: The MASS elements representing passengers.

Shell elements with lower values of elasticity modules and with hard to model connections to the steel frame of the bus, such as front, side windows and floor (plywood), were not involved in the bus FE models. Due to the fact that some other parts, such as windows, cabling, painting, interior stanchions etc., were not involved in the bus FE model, artificial values of mass densities were applied to match the weight of the bus FE models with the weight of the real complete bus.

The total number of elements in the FE models of the NEOPLAN RQ bus is 73 483. The number of nodes is 65 860.

The loading caused by the presence of standing passengers is converted from uniformly distributed load to the lumped masses. Positions of masses representing the standing passengers are shown in Fig. 8 (using blue color).

5. FE analysis results

The field of von Mises stresses on the NEOPLAN RQ bus structure was obtained from the linear static calculations for both the empty and the fully loaded bus FE model under vertical acceleration 9.81 $m \cdot s^{-2}$. Vertical support of the model was defined in the positions of suspension-frame connection. The resulting values were safely below the allowed limits.

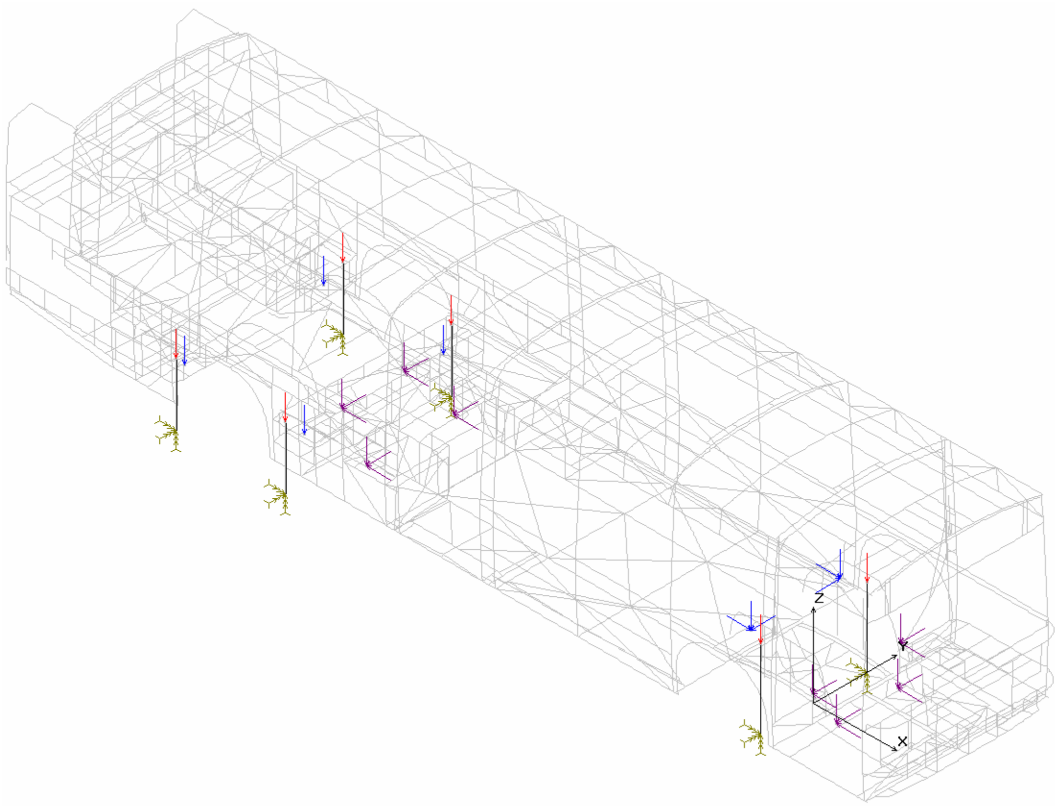

Fig. 9: Boundary conditions and acting forces used in the dynamic analysis.

The dynamic calculations were performed for both the empty and the fully loaded bus FE model version and run in two steps:

1. Calculation of the eigenvalues and corresponding eigenmodes.
2. Simulation of the bus running over the artificial standardized obstacle (time histories of the forces acting in axles' suspension elements and axial forces acting in axles' radius rods determined at multibody simulations are the input data) – solved as a modal time history analysis (see Bathe & Wilson, 1976 for details).

To assess the magnitude and the distribution of the stress response due to the dynamic load, the bus running over the obstacle was modelled in the same manner as at the experimental measurements at the bus driving on the artificially created test track according to the ŠKODA VÝZKUM road vehicles testing methodology (e.g. Polach & Hajžman, 2005). Excitation forces were defined by the above described multibody simulations.

The mode shapes corresponding to the natural frequencies up to the value 42 Hz were considered for the dynamic response calculation. Modal time history analysis was launched with the following parameters:

- Starting time of the analysis = 3.5 seconds.
- Ending time of the analysis = 8 seconds.
- Time step = 0.005 seconds (200 Hz).
- Newmark time integration method was used.
- Modal damping with damping ratio 0.1 was applied.
- For the purposes of post-processing only the odd time steps (100 Hz) between 4 seconds and 5.7 seconds were considered.

In Fig. 9 the boundary conditions of the FE model and the position of excitation forces are shown. The whole bus structure was supported by soft beams attached to the bus body in positions of air springs. The stiffness of these beams was set in order to separate natural frequencies of rigid body motion from natural frequencies of the bus body.

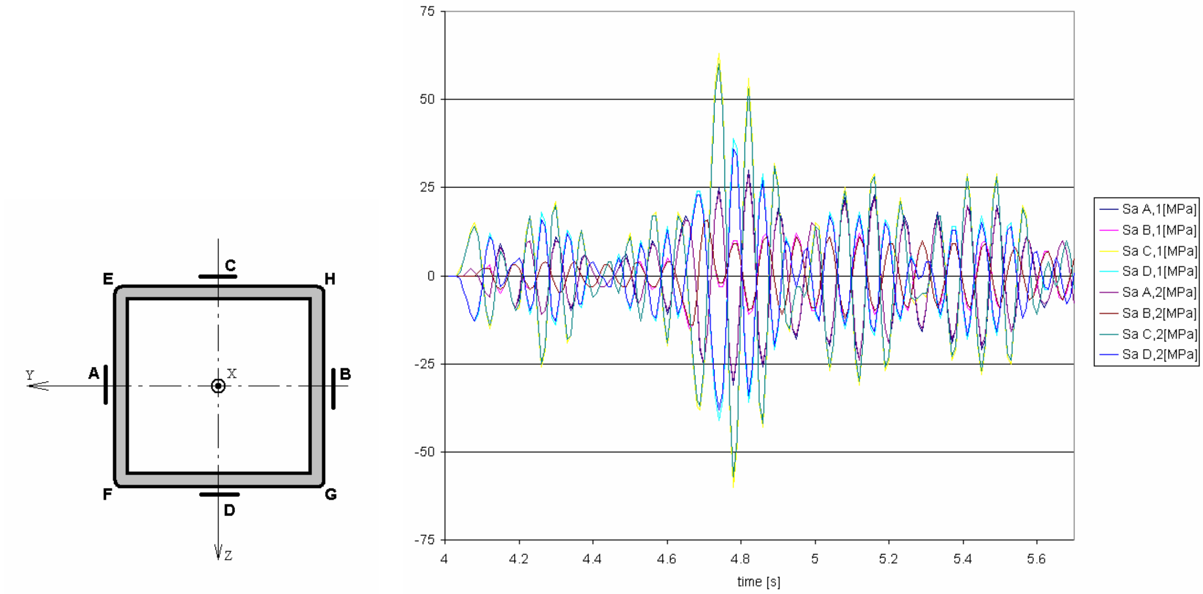

Fig. 10: Locations on a beam cross-section for stress evaluation and an example of stress time history.

A special in-house software has been developed for the evaluation of the results of dynamic calculations. This software completes the means of the postprocessors of the COSMOS/M software. To determine the critical points, the time histories of the stresses had to be calculated in all the possible places of the bus FE model. The time histories of the stresses on each side of the profiles of the bus structure had to be determined in every node of the element of the BEAM3D type (see Fig. 10). An example of stress time histories on the first and the second node of the beam is shown in Fig. 10.

From the time histories of the stresses in places A, B, C, D and node 1 or 2 (see Fig. 10), the following values were evaluated:

- σ_{max} maximum stress,
- σ_{min} minimal stress,
- σ_m mean stress,
- σ_a stress amplitude.

The locations for strain gauge placement were determined on the basis of the evaluation of maximum stress amplitudes for all beam elements. Then the experimental measurements on the real NEOPLAN RQ bus structure were performed at the bus driving on the artificially created test track according to the ŠKODA VÝZKUM road vehicles testing methodology (e.g. Polach & Hajžman, 2005).

6. Conclusion

In the paper multibody models of the (empty and fully loaded) NEOPLAN RQ low-floor bus (Polach, 2004) created in **alaska** simulation tool (Maißer et al., 1998) and finite element models of the (empty and fully loaded) bus body (Jankovec, Smola & Hejman, 2004) created in COSMOS/M software (SRAC, 1999) are described.

Simulations of running over the large road unevenness represented by the artificial obstacle of the height 60 mm (according to the Czech Standard ČSN 30 0560 Obstacle II) were performed with multibody models of both empty and fully loaded bus at driving speeds 40 km/h. Running over the obstacle with all the wheels, the right ones and the left ones were simulated. Forces acting in axles' suspension elements (i.e. in air springs and shock absorbers) and axial forces acting in axles' radius rods were the monitored quantities. Simulations results were used (together with time histories of directions of axles' radius rods considering the bus chassis frame) as input data for the calculations of the stresses of FE models of the bus body in the COSMOS/M software.

Static FE calculations revealed that Von Mises stress of the Neoplan RQ bus body is loaded bellow its allowed limit values.

Dynamic FE calculations of the driving over the artificial standardized obstacle revealed the places with higher value of stress loading. The strain gauge map was generated for the measurements on the real structure from the set of these critical areas in the bus structure.

It should be possible to extend the simulations with the NEOPLAN RQ bus multibody models by the simulations of further operational situations (e.g. braking, start, driving on the defined uneven road surface, a slow front impact against the concrete wall and driving manoeuvres – sinusoidal steering input, sudden steering angle change according to the ESV, severe lane-change manoeuvre according to ISO 3888-1, etc.) and by the investigation of behaviour of a driver and passengers in the course of various operational situations on the basis of possible requirements. The FE calculations could be extended by the roof overloading calculations, which are usually used to demonstrate the ability of the structure to withstand the roll-over accident. But due to the Neoplan USA Corporation bankrupt further improvement of the multibody and the FE models of the NEOPLAN RQ bus can be found only in the sphere of wishes.

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