TESTS AND COMPUTER SIMULATIONS OF ELECTRIC BUSES

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ABSTRACT

Electric buses (trolleybuses and battery buses) are an important part of transport industry in the city of Pilsen, Czech Republic. The buses are mechanical systems subjected to long-term variable operational loads, dynamic loads and impact loads in special cases. A combination of computational and experimental methods is the best way of finding technically and economically feasible solutions to the problems of operational strength, fatigue life and passive safety. The paper describes the procedures used in the development of SKODA electric buses.

Keywords: electric buses, strength, fatigue life, passive safety, computer simulations, laboratory tests, track tests

INTRODUCTION

If you consider the market prospects of a mediocre product, they will be poor or, at best, short-lived. The same holds for its manufacturer. By contrast, an outstanding product must remain reliable and safe throughout its entire operating life. Due to the pressure on manufacturing costs, an engineering design solution which provides optimum product weight is a must. This is the situation in the current environment where new structural materials keep emerging. In laboratories for basic research, these new materials seem to promise viable and advanced technical solutions for the future. However, unsuccessful real-world deployment may prove costly for the manufacturer, the user and even the society as a whole.

Is computational mechanics alone capable to provide an objective assessment of properties of a new product in real-world operation? The success of the use of numerical methods in designing, sizing and predicting the future behaviour of a structure, machine or a process plant depends on how the designer masters and combines experimental procedures, testing machines, instruments and methods for validating computational models and the acquisition of the input data for computation (identification of loading states in operation, experimental verification of the structure’s response, measurement of materials data and others). Industry sectors, where computation and experiments are inseparable, include automotive, aviation, rail transport engineering and power engineering. For decades, these sectors have been driving the development of engineering design and computer simulation software in various disciplines, such as strength analysis, kinematics, dynamics, fatigue life analysis, aerodynamics, thermomechanics and others. Hands-on experience and results achieved by world’s leading companies in traditional and emerging fields of industry prove that computational methods can only strengthen their position when combined with well-designed experiments. Authors of the present paper can confirm this statement thanks to their participation in remarkable development and testing projects involving complex novel engineering structures, predominantly in transport vehicle engineering.
STRENGTH AND FATIGUE LIFE

The combination of computational and experimental methods has earned its place in the development of complex products, among which one can certainly include electric buses (e-buses). The mechanical structure of a vehicle is a complex system which is subjected to dynamic loading of stochastic nature during service. Hence, one of the key objectives in the development a new vehicle is to design the body and the chassis, as well as their heavily-stressed structural nodes, for adequate strength. Unlike the producers of passenger cars, manufacturers of public transport vehicles do not normally have the opportunity to carry out final long-term tests on secret test tracks. This makes the effort invested in the computation, tests and their validation even more important.

Fig. 1 illustrates all development stages of the structure of a road vehicle for public transport (buses, trolleybuses) during the process (CAD, MBS and FEM models, functional sample, prototype, serial product).
In the first phase, a dynamic model of the vehicle is constructed using multibody simulation (MBS) software. It should include descriptions of kinematic linkages, inertia characteristics and elements of the vehicle suspension. A whole number of parameters need to be acquired or refined by means of laboratory testing and measurement. Using the MBS model of the vehicle, designers study dynamic excitation forces caused by the ride on an irregular road surface. They also map the vehicle’s response to various manoeuvres and assess its directional stability.

The strength characteristics of the vehicle’s load-carrying structure are investigated using finite element method (FEM) software. The computational models are derived from the vehicle’s design. Recently, the conversion of CAD data (Computer-Aided Design) to data formats for FEM tools helped to accelerate the communication between designers and computational engineers.

Using the FEM model, static calculations are carried out first – in order to determine the distribution of load across the structure. The loads are due to the vehicle’s own weight, the weight of main vehicle subsystems, and the passengers. In the next phase, the calculation aims at natural frequencies and modes of vibration of the vehicle structure and on the stress response to dynamic excitation forces, e.g. during the ride over a sizable irregularity in the road’s surface. By means of FEM, one can identify weak spots in the load-carrying structure of the vehicle and optimize them. Detailed FEM analysis typically focuses on those vehicle elements which transmit major dynamic operating forces. Key experimental techniques in the optimization effort are tests of entire vehicles in test rigs and laboratory tests of structural elements.

For rig-testing, the functional sample of a vehicle is placed onto loading cylinders of a multi-channel electrohydraulic loading system. Dynamic excitation forces and displacement are then imposed on the vehicle’s structure. The stress response and acceleration are measured by strain gauges in selected locations of the structure. The gauges can also be fitted to notch-like locations and other areas of high stress concentration. The advantages of these tests are the repeatability of loading states and the opportunity to evaluate the effect of structure modifications using the actual functional sample of the vehicle.

The purpose of the laboratory testing phase is to evaluate the fatigue strength and fatigue life of crucial structural components of the vehicle. The stress fields in both standard and complex-shape cross-sections of the particular structural element are measured by strain gauges. Simulated loading states which correspond to actual service conditions are imposed for this measurement. Static testing is followed by fatigue tests, in which the structure is subjected to cyclic load. Their results also reflect the effects of the particular manufacturing process and its quality, which is something the computational models cannot provide. Based on the outcomes of laboratory testing, the manufacturer can improve the structure’s fatigue resistance to prevent in-service failures.

The actual service load levels are typically verified on the first prototype of the vehicle. For this purpose, strain gauges are attached to all key parts of the vehicle’s structure and the stress response to the ride over irregular road surface is measured. The load magnitudes are typically determined on empty and fully-occupied vehicles. First, the maximum dynamic stress levels are evaluated, while the vehicle rides over a sizable irregularity – an artificial obstacle. Stress plots for the structure’s most heavily-stressed locations are recorded during long rides on roads with irregularities. Fatigue strength can be predicted for critical locations of the structure from the analysis of stress vs. time plots. The safety against fatigue damage can be evaluated.
This method brings together tools of computational and experimental mechanics, as shown schematically in Figs. 2 and 3.

Fig. 2 - Evaluation of service and fatigue strengths – calculation procedure
Fig. 3 - Evaluation of service and fatigue strengths – experimental procedure
The combination of calculations and experiments is equally indispensable to the optimization of structural nodes and parts of vehicles. Furthermore, optimization must take into account the effects of manufacturing processes on materials properties degradation. This is illustrated in Figures 4 and 5.

Fig. 4 - Optimization of a structural node – combined use of computational and experimental mechanics
Fig. 5 - Optimization of a vehicle’s component – combined use of computational and experimental mechanics
PASSIVE SAFETY

In order to develop relevant requirements for passive safety, it is essential to identify standard or representative situations, in which road accidents occur. The bus body structure must have sufficient strength so that the passive safety system can prevent – during and after the accident – serious injuries to those involved in the accident. Each passive safety specification therefore starts with a detailed summary of data on road accidents.

Fig. 6 outlines the principles of ECE R66 regulation which came into effect as early as 1986 and which deals with the roof strength. It describes a road accident situation (rollover) in terms of simple tilting and subsequent fall from an 800 mm-high platform onto concrete surface. The deformation of the door and window posts is measured to assess the strength of the structure and the preservation of the residual space.

Fig. 6 - Principles of the R66 regulation – preservation of the survival zone upon the rollover of a vehicle

Palata et al. from the company Vision Automotive Consulting Prague (www.vca.cz) developed a method which combines computational and experimental mechanics. The method includes the following:
• The use of FEM software for computing large strains in the region of non-linear dynamics,
• Measurement of mechanical properties of the materials of sections used for building the vehicle body,
• Computer simulations and experiments on sections used for building the vehicle body,
• Computer simulations and experiments on subassemblies of the vehicle body,
• Optimization of computational models to refine the materials property data, to improve the mesh and to account for the effects of the manufacturing process,
• Final computer simulation of the rollover of the entire vehicle.

The behaviour of the material is described using a model which takes into account work hardening. The model relies on materials data from conventional tension testing. The tension tests are carried out on flat specimens of the base material of the sections used in the vehicle body, see Fig. 7.

![Fig. 7 - Measurement of fundamental mechanical properties of materials](image)

The next stage involves research into and refinement of materials data. This is important to exploring the decisive deformation mode of vehicle body sections during the rollover test. All critical sections of the vehicle body undergo bending tests (Fig. 8). The load rate is in the range of the rates expected during the rollover test of the entire vehicle. Concurrently, computational modelling of the same process takes place. Its results are compared with the experimental data and the material constants are updated and the mesh is optimized accordingly.

The materials parameters and the mesh used in the computational model are finally validated against data obtained from experiments on vehicle body subassemblies supplied by the manufacturer for the rollover test (Fig. 9). Thanks to this validation, the computational model incorporates the effects of the vehicle body manufacturing process (e.g. welding).

The computational model refined in this way is used in the rollover simulation of the entire vehicle (Fig. 10). The compliance of the load-carrying structure of the vehicle with the ECE R66 regulation is reviewed. According to this regulation, the columns must not enter the pre-defined survival zone. If the outcome of the computation is unsatisfactory, the designer has to optimize the structure. In some cases, the body structure must be modified (e.g. by increasing the thickness of the column sections), in other cases, alterations to details are sufficient (changing the stiffness of the joint between the columns and the sections of the roof and other modifications).
Fig. 8 - Computer simulations and experiments on sections used for constructing the vehicle body

Fig. 9 - Computer simulations and experiments on a subassembly of the vehicle body

Fig. 10 - Final assessment of the vehicle’s structure by means of computer simulations
The aforementioned method was verified by a full-scale test of the structure of a low-floor SKODA 21Tr trolleybus, as illustrated in Fig. 11. It is also an excellent example of an appropriate utilization of computational and experimental techniques. In the procedure, computational models are validated step by step at various levels of the structure’s complexity.

Fig. 11 - Validation of the computational-experimental procedure for strength evaluation of the load-carrying structure of the body of a trolleybus according to R66 regulation

Electro-mobility is an increasing trend across the globe, a trend which occurs in the Czech Republic as well. The emergence of battery-powered electric buses opens a new field of research. In these vehicles, the passive safety has new and rather specific aspects. Some requirements for passive safety of parts of electric buses have already been set out in the European EHK100.2 standard “Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train”. The RESS (Rechargeable Energy Storage System) poses a considerable risk in the event of a collision between a battery-powered electric bus and a massive obstacle. Now, the EHK100.2 European standard also provides for the resistance to mechanical impact. The requirements for testing the RESS are defined unambiguously. The purpose of the test is to verify safety in a road accident (impact of the vehicle). In the test, the RESS or a related subsystem is subjected to an acceleration pulse. This acceleration pulse is defined separately for longitudinal and transverse directions in the form of a band between maximum and minimum values (Fig. 12).

Fig. 12 - Acceleration band for vehicles of M3 and N3 categories
Since the testing required for the vehicle approval is very costly, one can expect computer simulations in this field to flourish. This is the task with which authors of this paper have dealt in relation to the development of SKODA battery-powered buses.

The Pam-Crash software was used to investigate the dynamic process. FEM-model of the RESS and the adjacent segments of the body in the front and rear parts of the e-bus was developed. The model of the RESS structure was very detailed with idealized welded and screw joints. The approximate weight of the RESS is 750 kg. Each RESS contains three slide-in modules with accumulators designed as independent units. 2D elements with four nodes and 3D elements with eight nodes were used. Their size was set at 10 mm (with regard to the acceptable time step). The model of the rear portion of the e-bus is shown in Fig. 13.

![Fig. 13 - FEM model of the rear part of the battery-powered bus](image)

In order to obtain good agreement between the FEM model and the actual physical process, mechanical properties of the materials were measured. The electric bus components of interest were made of S235, 1.4301 and S355 steels. Their mechanical properties were measured using tension and micro-tension tests to map the behaviour of materials at various strain rates (0.015; 1.5; 15; 150 s\(^{-1}\)). The effect of the welding process on the properties of the material was studied by means of tension testing of welded specimens.

The quantities monitored are the total energy of the model and the hourglass energy. The characteristic property of a structure undergoing plastic deformation is its ability to absorb energy. The criterion studied most closely was the occurrence of plastic deformation. For the structural integrity to be preserved, the plastic deformation must not exceed the critical limit, beyond which the material may fail. Results of the calculations are shown in Fig. 14. The largest plastic deformation is found at the attachment points of the RESS to the e-bus structure.

The behaviour of the e-bus structure during the acceleration pulse according to EHK100.2 exhibits a notable dynamic response. The simulation revealed large displacements in massive parts. The strain rate in the most heavily-loaded locations is below 50 s\(^{-1}\). The effect of work
hardening in the materials of interest at higher load rates did not prove to be significant. The impact of inertia forces is much heavier. Plastic deformation was found to occur only locally. Its magnitude does not mean any risk of failure. The structure of the e-bus is capable of absorbing much more deformation energy than the amount considered in the simulation.

Fig. 14 Maximum plastic deformation levels at critical nodes of the bus structure (attachment of the RESS)

CONCLUSIONS

The methods described in this paper were successfully applied in the development of several types of SKODA electrobuses (trolleybuses and battery buses). General principles and parts of the methodology were used in the cooperation with other producers of road vehicles (Neoplan US, Karosa / Iveco Czech Republic, Ikarus SCF, and others).

The two-way transfer of know-how between research institutes, technical universities and industry has proven to be an effective tool for achieving the following aims:

a) Interconnection of knowledge from basic and applied research with that from industrial development.

b) Integration of practical knowledge from industrial research and development into the instruction at technical universities.

New research projects are already running at the University of West Bohemia and others are under preparation:

- Fatigue post-processing of FEM calculations.
- Long-term measurements with telemonitoring and wire-less data transmission.
- Electronic catalogue of existing S-N curves of both materials and components.
- Application of the probabilistic approach in calculations of operational reliability of fatigue-loaded structures and their parts.
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