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DYNAMIC TESTING OF BUSES AND THEIR COMPONENTS

PETR ZÁRUBA
TÜV SÜD Czech, Novodvorska 994/138, 142 21, Prague, Czech republic, +420 607 068 202, petr.zaruba@tuv-sud.cz

JAKUB JELÍNEK, MICHAL KALINSKÝ
TÜV SÜD Czech, Novodvorska 994/138, 142 21, Prague, Czech republic, jakub.jelinek@tuv-sud.cz, michal.kalinsky@tuv-sud.cz

ABSTRACT
The article gives an overview of a virtual simulation method under ECE Regulation No. R66 – bus rollover. The first part of the article introduces the process of virtual simulations in terms of homologation. The conclusion is focused on the correlation of physical tests with virtual simulations.
KEYWORDS: ECE NO. 66, ROLLOVER TEST, FEM ANALYSIS, CRASH, PHYSICAL TESTING, VALIDATION, AUTOMOTIVE, TÜV SÜD CZECH

SHRNUTÍ
Článek se věnuje problematice virtuálních simulací dle předpisu ECE No. R66 – převrácení autobusů. V jednotlivých kapitolách je rozebrán postup virtuálních simulací z pohledu metodiky a homologačního procesu. Závěr je věnován korelaci fyzických testů s virtuálními simulacemi.
KLÍČOVÁ SLOVA: EHK 66, PEVNOST KAROSERIE, PŘEVRÁCENÍ AUTOBUSU, MKP ANALÝZA, DYNAMICKÉ DĚJE, FYZICKÉ TESTOVÁNÍ, VALIDACE, AUTOMOTIVE, TÜV SÜD CZECH

1. INTRODUCTION
Every year sees an increase in the requirements for passive vehicle safety, and not just in the personal vehicles category, but also for public transport vehicles. TÜV SÜD Czech has been certifying M2 and M3 category buses (single deck rigid or articulated vehicles) according to European regulation ECE R66 – Strength of the chassis large bus, for several years. Regulation ECE R66 is one of several homologation regulations which can be certified by virtual simulation. Virtual simulations are very much required with this regulation, because physical tests take a long time to perform and do not allow many iterations of conceptual design within a very short timeframe.

2. REGULATION ECE R66
Regulation ECE R66 entered into force in 1989. In 2005, a series of changes included more detailed approval procedures using virtual simulations. Regulation R66 requires a manufacturer to construct the chassis of vehicles that will carry more than 22 passengers including driver strong enough so that a survival space clear of any penetration by internal primary structure is preserved when it falls from a platform. This survival space for passengers and driver is defined by the floor structure, the inner cover of the main load structure and by definition of the SR point on the seat, see Figure 2. The test is performed with only half the mass of all passengers, which is 34 kg per passenger, located 100mm before and above the R point of the seat. This stricter regulation with added mass is described in R66.01 only for newly certified vehicles with effect from November 2010. In November 2017, however, a new version of regulation R66.02 was introduced that extends compliance with this regulation to smaller buses (16+ passengers).

3. CERTIFICATION PROCESS USING VIRTUAL SIMULATION
The process of certification by virtual simulation requires the time consuming and sophisticated preparation of a numerical model. This method depends on having the full set of data

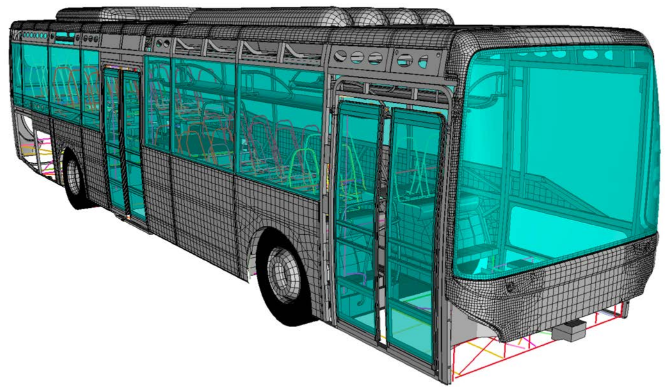

FIGURE 1: FEM model of bus
OBRÁZEK 1: MKP model autobusu

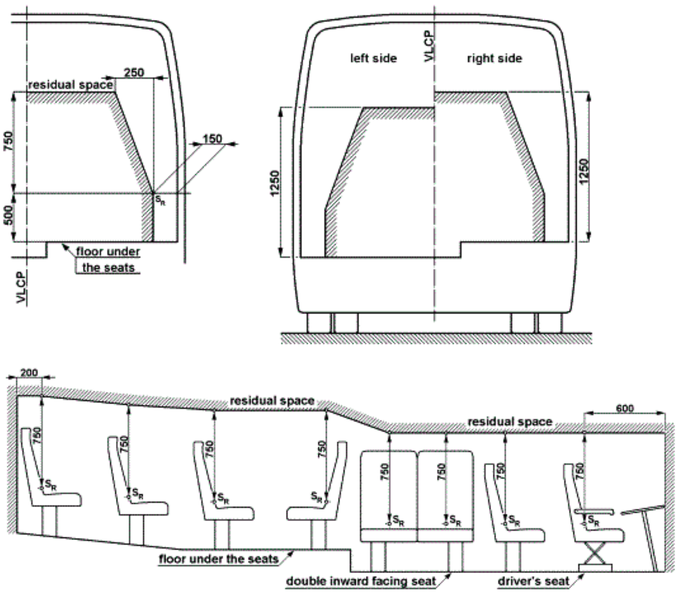

FIGURE 2: Survival space template
OBRÁZEK 2: Vymezení prostoru pro přežití

from manufacturer, such as 3D CAD data, real mass of bus components, exact position of the center of gravity, and material characteristics. From the certification point of view the manufacturer may place on the market several variants of the same vehicle type for different numbers of passengers. For this type of global approval, the worst-case configuration for the rollover strength test is considered for the calculation as it covers all other less severe designs. This is the construction with theoretically the worst deformation. The basic structural elements of bus construction are steel beams on the side of the bus and it is, in particular, the number of these beams that determines the stiffness of bus during rollover. From experience the worst variants are those that have a lower number of side beams and the highest center of gravity. When the CoG point is high on the Z axis, the impact energy and angular speed is also increased and causes bigger deformations. To determine the worst variants, a method based on the calculation of the impact energy and its relationship to specific columns with the inclusion of the cross-sectional characteristic is used. The variant with the highest energy at the column is deemed the worst case.

With the updated version of the regulation, the standard now also applies to buses with low transport capacity. These vehicles are conceptually very different because they use self-supporting or additionally reinforced van structures, see Figure 3. For these vehicle types it is very difficult to use the simple principle of relative strain energy on a pillar adopted for conventional buses. The choice of the most critical variant is determined primarily by the position of the center of gravity, the transport capacity and the equipment of the bus – its operating mass.

The chassis of these bus types (vans) do not perform at their best during the R66 test. The main objective of bus manufacturers is to maximize transporting capacity and, with a typical number of 30 passengers, the vehicle mass of a tested vehicle is increased by more than one ton of additional mass. This is in some cases almost a quarter of the mass of the structure, which is located above the original center of gravity. Compared to large buses, it is much more difficult to feasibly design this type of vehicle from the manufacturer's perspective given the complication of adding additional beams into the existing structure.

The manufacturer is required to submit the necessary documentation for this vehicle variant. Then the certification process takes place according to the internal methodology. If a manufacturer cannot provide the testing laboratory with approved material data sheets, the window beams have to be physically tested and a material model developed. Several tests have to be carried out and these are quasi-static tensile tests, bending tests and dynamic drop tests. Dynamic drop tests are primarily performed to determine the response of a material during impact. The mechanical properties of the material vary with the load speed (the strain-rate effect). This

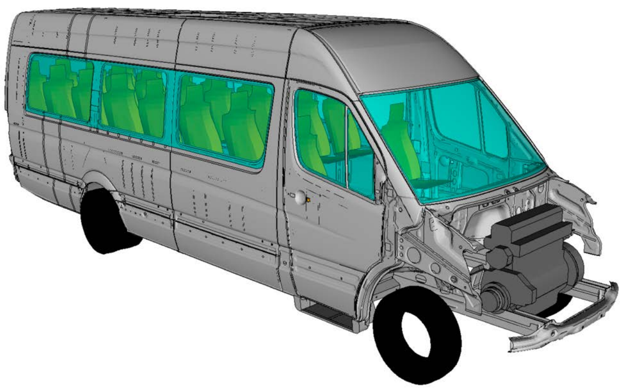

FIGURE 3: Van type of vehicle
OBRÁZEK 3: Autobus založený na podvozku dodávky

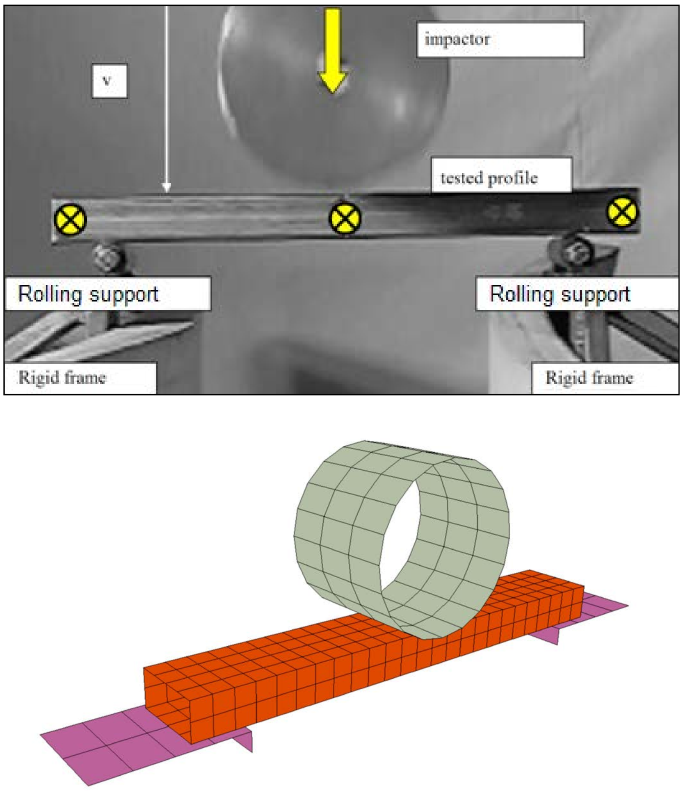

FIGURE 4: Drop test physical and virtual representation
OBRÁZEK 4: Pádová zkouška fyzická a její virtuální reprezentace

drop test is performed on the characteristic piece of window pillar that the impactor strikes. The impact energy during the test corresponds to the energy in the real test of the entire bus. In the PAM-Crash simulation software, this test is then replicated and based on the deformation evaluation using the video sequence, the numerical model is validated for the drop test.

In the case of small buses, the drop test is applied for more complex parts of the structure. These can, for example, be stamped parts, parts made by hydroforming etc. An example of the drop test for a bus A-pillar of is shown in Figure 5. It should be noted that the evaluation and subsequent tuning of the properties of a material model is more complex because deformations occur in several directions. In this case the deformations are measured using 2D tracking points, and plastic deformation is measured after impact by photogrammetry. For validation it is necessary examine the pillar behavior using video footage from a high-speed camera.

The creation of a numerical bus model is very time-consuming. It takes one full-time employee about four weeks to prepare a finite element (FE) model of an 18m long bus, and another two weeks is spent connecting and setting up the model.

In terms of computational time saving, a 3D CAD model that includes volume geometries is converted to mid-surface and the thickness is assigned to 2D elements only computationally. For computation purposes, 2D shell elements are used with five integration points using the Bellytschko-Tsay uniform reduced integration method. For steel materials, material model type 103 is used – Elastic Plastic Iterative Hill with Krupkovsky Law coefficients. A 3D model also contains a number of radii and holes unnecessary for R66 testing. Holes with diameter smaller than 1/5 of the smallest edge are removed and replaced by a mesh (elements), as are radii smaller than 1/5 of the smallest edge.

Welded joints are largely represented by coincident mesh nodes. This representation method is sufficient and creates smaller strain concentrators than other types of entities. In cases where the direct connection of mesh nodes cannot be used, the welds represent the entity characteristic of PAM-Crash, Plink. For predictable results on all models it is necessary follow the mesh quality and element sizes of the validation model. On parts belonging to the main structure, such as pillars, we use an element size of 8mm, which offers an acceptable combination of size (in terms of computation time) and accuracy. The internal criterion for minimum element length is 5mm for a model consisting of under 1 million elements. It is necessary to keep as many QUAD elements as possible in order to reduce stress concentrators, which are produced by inconsistent mesh with bad quality elements.

When the model is prepared, initial conditions and non-structural masses are added together with the mass balance with respect

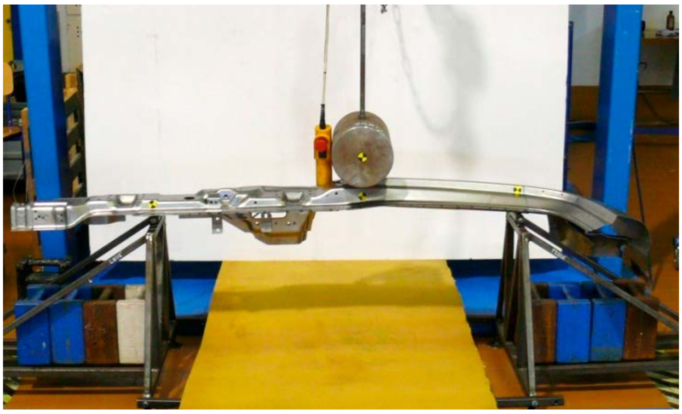

FIGURE 5: Drop test of an A-pillar
OBRÁZEK 5: Pádová zkouška A sloupku

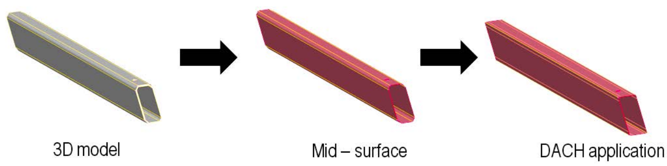

FIGURE 6: Pillar FEM model preparations
OBRÁZEK 6: Příprava MKP modelu sloupku

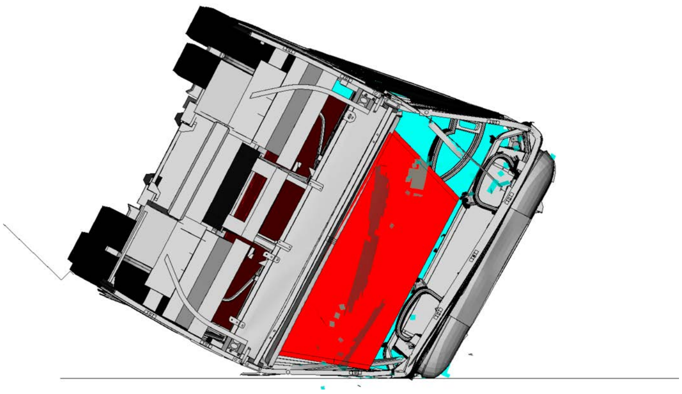

FIGURE 7: Bus rollover
OBRÁZEK 7: Převrácení autobusu

to the center of gravity. The position of the center of gravity in the Y and Z direction is very important for the simulation. It determines the unstable position when the platform is tilted. From the center of gravity values, this unstable position can be calculated and then the impact angular velocity determined. The accuracy of results is given by the impact kinetic energy of the model calculated from the moment of inertia and angular velocity. The evaluation of the R66 test is rather straightforward. If any part of the internal structure penetrates the survival space, the test is unsuccessful and structural changes are required.

4. CORRELATION PROCESS

To evaluate the results of the numerical simulation, the validation of partial results is necessary. These validations are performed as the numerical model is being created. Individual components are tested both quasi-statically and dynamically as indicated beforehand. One of the purposes of validation is determination of a suitable method for creating a mesh when connecting beams with different cross sections. The purpose, for example, of T-joint weld connections is to find an adequate simplified weld representation. These connections

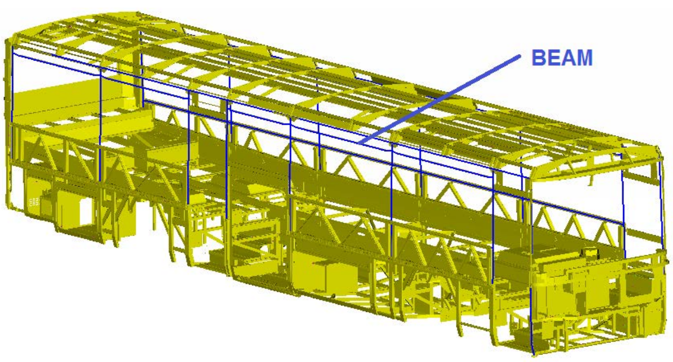

FIGURE 8: T joint with variable pillar height and difference between the PLink joint and connecting of adjacent nodes
OBRÁZEK 8: T spoj s proměnnou výškou profile a rozdíl mezi spojením typu PLink a napojení sousedních uzlů

are difficult for the numerical model due to the problematic joining of coincident nodes.

The most obvious variation of homologation simulation results is the physical examination of the bus segment. The segment must represent the main structure of the bus chassis, where the R66 test is performed. The most important result is the measurement of the maximum as well as plastic deformation, together with the determination of plastic joints and cracks. The deformation of an entire segment is measured with potentiometers located at the important points of the construction. From these measured points the deformation is evaluated. Tests are also captured with high-speed cameras, from which it is possible to determine the behavior of the test sample and deformations are evaluated using a photogrammetric method (2D). Accelerometers and other devices can also be used for validation, but this is optional and not every project definition requires such a detailed approach. One of the specialized measurements is, for example, strain gauges placed on washers for the measurement of axial forces in the bolts. These washers are calibrated for axial loads on the tensile test.

5. SIMULATION TEST PARAMETERS AND MEASUREMENT UNCERTAINTIES

Physical and virtual test results may be a little different due to model uncertainties. If we include all the model uncertainties of the virtual process and the physical validation, we obtain a total uncertainty in the region of ~ 20%. Some uncertainties are caused due mistakes in physical measurement and some come from numerical errors during computation. For example, a slight uncertainty is derived from running the computation on separate processors (parallelization) where each processor has an uncertainty in rounding. So, if computation is split between several processors, it can happen that a slightly different result is obtained with the same simulation. From experience, results from models prepared and validated in PAM-Crash software are slightly more conservative and show worse results when compared to the physical tests. In the case of homologation calculations, we are on the conservative, i.e. safe side. The calculation results are very dependent on several basic parameters, such as mass, position of the center of gravity, vehicle moment of inertia and impact velocity. There are also many other numerical parameters. Among these parameters are, in particular, the coefficient of friction between impact area and tested model. The coefficient of friction must be measured for a specific impact area and given in the technical protocol. Figure 9 shows differences between friction coefficients. The Y axis indicates the distance of the B pillar from the survival space template. With the improved friction coefficient of real concrete and steel (red line) there is greater deformation – it comes closer

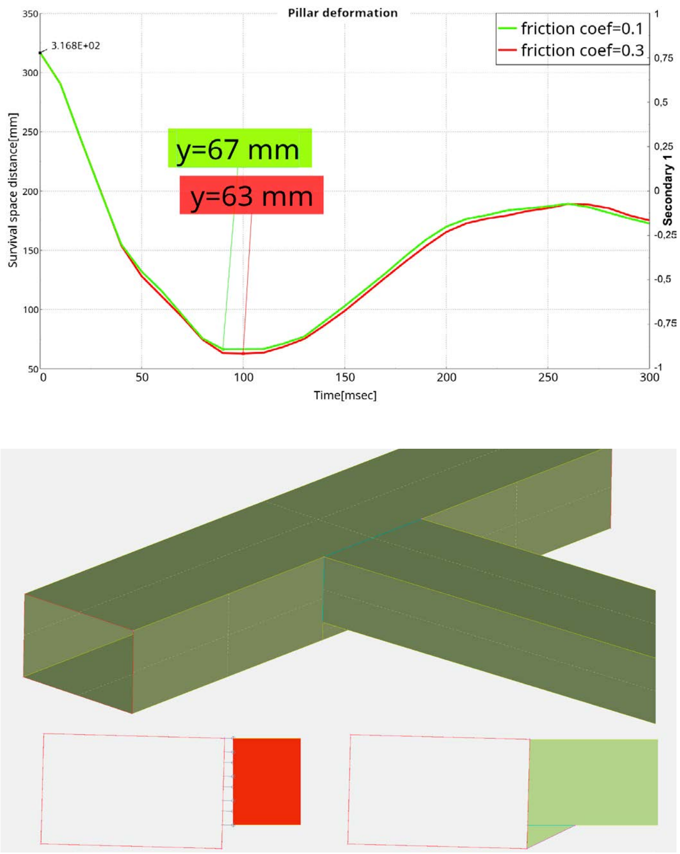

FIGURE 9: Distance of survival space template and B pillar in relation to friction coefficient
OBRÁZEK 9: Graf vzdálenosti prostoru pro přežití a B sloupku v závisloti na třecím koeficientu

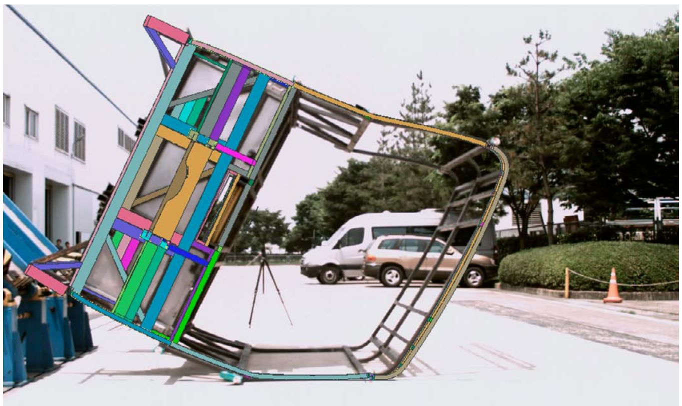

FIGURE 10: Illustration of physical test validation
OBRÁZEK 10: Korelace fyzického testu a virtuální simulace

to the survival space template. Also, the friction coefficient changes the behavior of the whole rollover.
Boundary conditions are set according to the ECE R66 regulation. This means that applied to the model is gravitation and initial angular velocity. The simulation doesn't run through the whole rollover, but computation starts a few centimeters before first contact with the ground. Initial conditions are calculated from the unstable position.

6. CONCLUSION

Based on correlations between the physical tests and virtual simulations, the Czech Accreditation Institute (ČIA) acknowledged the internal methodology and subsequently accredited the Department of Virtual Simulations of TÜV SÜD Czech for the virtual testing of bus constructions according to R66. TÜV SÜD Czech performs about 15 virtual and 5 physical tests per year. There also remains great interest in the testing of entire buses. These tests have moved from pure homologation tests more to validation FE analysis, and are supporting the manufacturer's R&D department. The requirements for measurement equipment and post processing have increased, due to increased test complexity.
In conclusion, however, it is important to note that progress in virtual testing has increased, but it still cannot completely replace physical testing. The best option for the testing departments, and also for the customer, is a suitable combination of both approaches. Final homologation can be achieved faster, more effectively and with lower cost. The bus design can be optimized and adapted to load conditions while maintaining all other operating parameters.

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