EUROPEAN TEST METHODS FOR SUPERSTRUCTURES OF BUSES AND COACHES RELATED TO ECE R66 (THE APPLIED HUNGARIAN CALCULATION METHOD)

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ABSTRACT

The first full-scale roll-over tests of coaches and buses, in Europe, have been started at the beginning of 70's in Hungary. Later in 1986, the European Committee of Economy has accepted and issued a new regulation related to the bus and coach superstructures' strength.
The previous methods and all the four test methods, accepted in the ECE R66, are discussed technically and critically in this paper.
The recently used combined Hungarian method based on quasi-static tests of bus-frames and simplified computer simulation of roll-over process is presented too.

BÉLA BARÉNYI, THE CREATOR OF MODERN PASSIVE SAFETY

The Hungarian-Austrian born automobile constructor Béla Barényi (1907-1997) was the *Nestor of vehicle passive safety* of our modern time. His predominant activities have served the Daimler-Benz.
The concept of passive safety originates from his patent of "Front and Rear Impact Zones" in 1951. (The division of vehicle safety into two parts: passive and active safety is firstly published by an Italian journalist Luigi Locati in 1964.)
Two basic patents of Béla Barényi related to our theme can be emphasized: Rollbar (1949) and Multiple-Purposed Safety Roof (1955) for automobiles.
His name, as an outstanding inventor of our age, can be rightly read on the wall of "Automotive Hall of Fame" in Midland, Michigan.

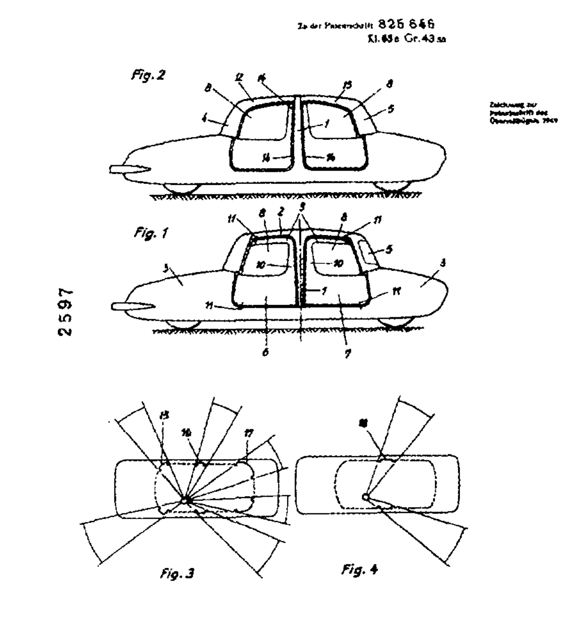


Fig. 1. Patent of Béla Barényi: Protective rollover bars for automobiles (1949). First application was at Porsche 911 Targa in 1967.

BUS ROOF STRENGTH RESEARCHES IN HUNGARY

Passive safety researches of buses and coaches has been started at Ikarus Co. in Hungary at the end of 60's effected by the next coincidences:

- serial production of IK 200 bus-family has claimed new demands from the world's largest bus manufacturer and in the same time the development work of national (Hungarian) technical specifications for buses has been also started;
- several fatal home accidents have pointed out the weakness of coach and bus superstructures and the necessity of more rigorous passive safety requirements;
- initiative of the world-wide ESV program.

What kind of basic accident situation were examined?

- fall down from overpass,
- rollover on a slope.

In both situations the longitudinal speed was neglected for the better repeatability. The research process was concentrated on three principal elements:

- to work out a standard accident situation,
- determination of a so-called survival zone for passengers,
- to develop approval methods for substitution of full-scale test.

Basic necessity for these is to determine a well-conditioned *standard* or *representative accident situation*. The vehicle shall have sufficient strength to ensure that during and after the given accident situation the examined passive safety system of coach or bus protects the occupants from injury. Therefore the detailed data collection of accident is the starting point of each passive safety specification.

Beside the officially used static kerbweight loading of bus and coach roofs, comparative test series were carried out with the coaches of IK 55 and IK 255 between 1970 and 1972 in Hungary:

- quasi-static tilting tests on the ground
- and real turnover tests on different slopes.

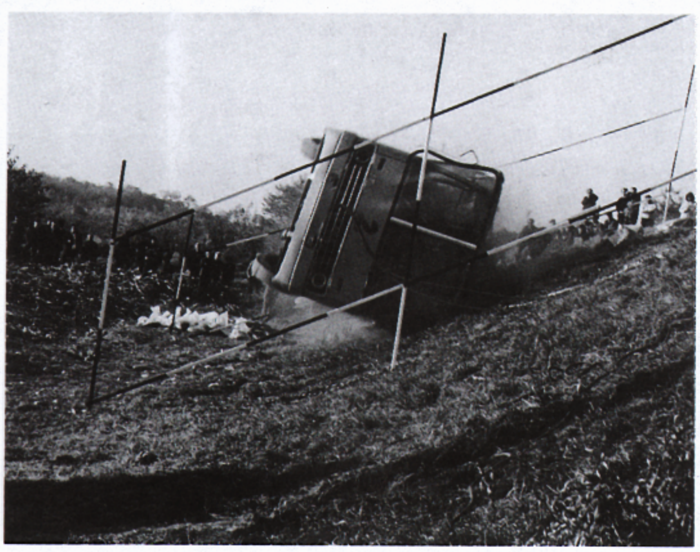


Fig. 2. After the fullsteal structural automobile's rollover tests in 1930, Hungary was the first to carry out real rollover test with complete bus in 1972. The test was accomplished with different reinforced compartments of IK 255 type bus on a 6/4 (33,6°) slope.

Fig. 3. This 1983's rollover test of Ikarus 255 bus demonstrated the applicability and repeatability of this kind of dynamic test method.

Hungary has played pioneer role in the development of the test specifications for coach rollover safety.
The actuality and importance of this subject was shown by the fact, that Britain, accepting the basic concept, had developed an own test method too. At the end a simplified common British-Hungarian rollover method was accepted as the new European Regulation ECE R66 in 1986.

EUROPEAN REGULATION ON BUS AND COACH SUPERSTRUCTURE'S STRENGTH - ECE R66

The superstructure of the vehicle for passengers' surviving shall be of sufficient strength to ensure that during and after the standard rollover accident situation no displaced part of vehicle intrudes into the residual space or projects outside the deformed structure.
Each type of vehicle carrying more than 16 passengers shall be verified on the basis of a full-scale rollover test or according to an alternative method approved by the competent authority.

This regulation allows four different methods given possibility for the Type Approval of vehicles:

- Full-scale rollover test on a complete vehicle;
- Rollover test on body segment or segments;
- Pendulum test on body segment or segments;
- Verification of strength of superstructure by calculation.

All of these four methods were carried out at AUTÓKUT in Hungary.

Full-scale Rollover Test

The vehicle with unladen kerb mass (explosive or corrosive materials may be substituted) should be rolled down from 800 [mm] height to a horizontal concrete surface without any dynamic effect. The axis of rotation is parallel to the longitudinal axis of the coach.
Seven coaches of three countries were tested till this time at AUTÓKUT in Hungary.

Fig. 4. General arrangement of full-scale test according to ECE R66. A computer controlled hydraulic system with multistep actuators is the basic equipment.

Fig. 5. Usual deformation shape of the superstructure after rollover test from 800 mm height.

Rollover Tests on Body Segment

It was the finally suggested alternative test method for checking of bus roof strength.
Using one or more rings with shorted exact cross-sectional geometry and mass distribution of buses or coaches you can carry out the rollover tests on this kind of segments, having modeled and represented all the main load-bearing beams and columns of bus compartment.

Fig. 6. Rollover test on a contracted multiple ring of IK 255 bus in 1985. This 2,5 m long, 8120 kg frame-segment contained 2 reinforced rollbars and 2 window-rings. (There was used a wood-surface.)

The main conclusions of the segment's rollover test were the next:

- the tested segment shall contain all the essential energy-absorbing elements (seat-frames, sheet-coverings,..);
- the tested segment shall be capable to absorb at least 80 % of the energy of the complete bus;
- main dimensions, mass distribution shall exactly be the same as at the original complete bus;
- the genuine manufacturing technology is very important.

Pendulum Tests

The fulfillment of requirements of rollover safety can be verified by pendulum test according to the text of Annex 5 of Regulation No 66.

At the moment of impact the direction of motion of the pendulum makes an angle of 25 degrees to the longitudinal vertical plane of the body sections.

The tested body sections were designed to be symmetrical to the vertical cross plane, not to cause any rotation of pendulum. Attachments of the sections to the mounting base are different, the only common feature is that each of them were fixed at the floor level with shape-closing link to the mounting base. The total energy to be divided to different body sections is equal to the energy of complete vehicle to be tilted from 800 [mm] height.

At AUTÓKUT a test series was carried out with eight double frame sections, one of them is shown in Fig. 7, and the comparison of this qualifying method to the complete vehicle rollover test has implied the next critical remarks:

- Anchorage, attachments of sections are not unambiguously determined and the absorbed energies depend on these.
  (Fixing at the upper level of underfloor cross-beam gives different result as the fixing at the lower level of underfloor structure.)
- The change of the impact force during the collision process is the opposite of that of the complete rollover test.
- Extra weights on the roof additionally increase the energy to be absorbed during the pendulum test according to the requirement, in contrast to the full-scale test where, in such a case the energy dissipated by pillars is lower.
- Different impact investigations regarding to the coach structures prove that 25-45% of initial impact energy avoids our measuring system of the deformation energy and leaves the tested system as noise, heat energy and mostly as vibration-wave through the fixings and the ground! This percent strongly depends on the fixings and makes uncertainties in the final calculations.

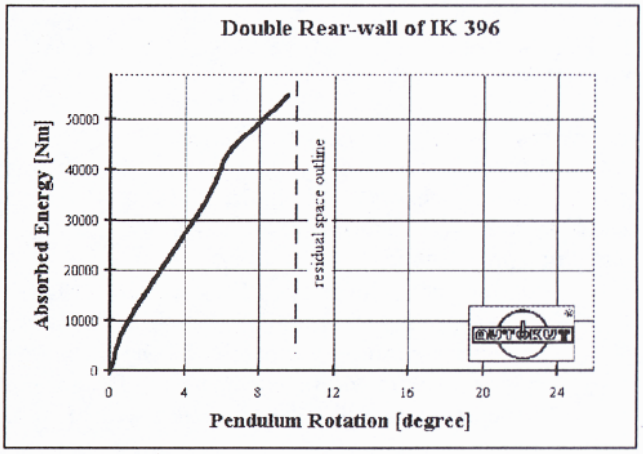


Fig. 7. Pendulum test on a double rear-wall segment of bus IK 396. The results of quasi-static laboratory bending test and the pendulum test indicate big differences on the same segment.

Numerical Calculation

The Regulation allows to carry out the type approval process by mathematical calculation based on the needed measurements of vehicle elements or segments. This is probably the fastest and perhaps the cheapest but the most arguable method.

THE APPLIED HUNGARIAN CALCULATION METHOD

On the basis of the previously carried out full-scale rollover tests and special quasi-static tests of relevant coach frames the Vehicle Mechanics Laboratory of AUTÓKUT has developed a new calculation algorithm in 1989.

The principle is simple:

- During the rollover test of a complete vehicle the cross-sectional rings of the superstructure determine the energy-absorbing capability of the whole coach. Rings contain cross members of underframe structure, side wall columns, window (door) pillars, roof ribs.

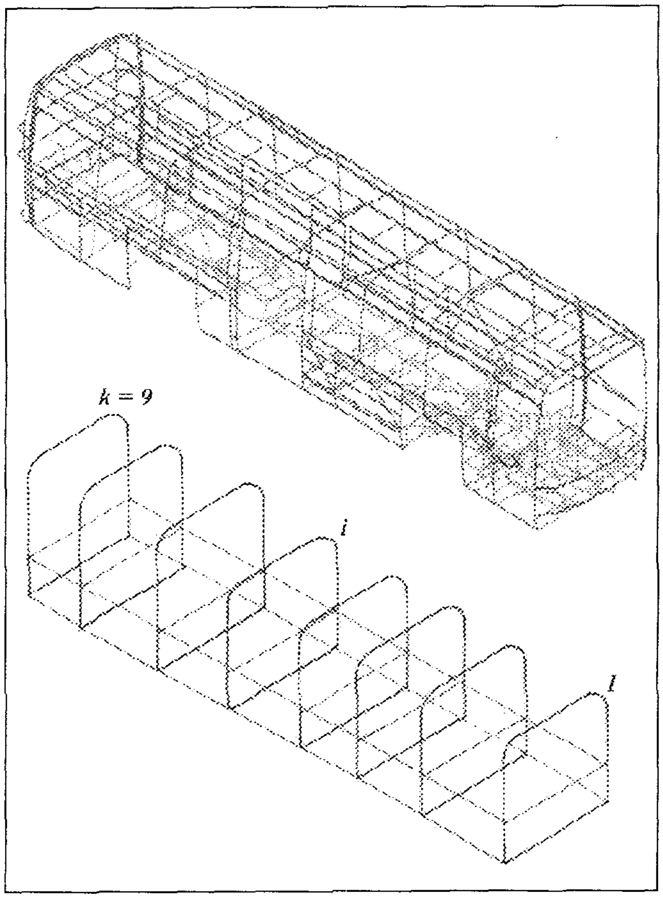


Fig. 8. Each bus or coach can be modeled with plane cross-sectional segments.

- These cross-sectional rings -excepted the front and rear walls- can be modeled with perfect plane-frames. The front and rear parts of coaches as extended sections also can be substituted with plane-frames measuring the bending stiffness and rigidity of the original front-wall - driver cabin and extended rear wall units. Geometrically the substitutive plane-frames can be positioned into the center plane of bending stiffness for the expanded sections.
- Basic condition: the roof cantrail has to be remained in straight line during the deformation process!
- 'k' pieces of coach cross-sectional rings as deformable units are substituted by 'k' pieces of non-linear springs in the mechanical model.
- Torsion displacements of rings may be neglected due to the (coach)chassis torsion rigidity. In spite of this the exact approach of the algorithm considers the non-infinitive rigidity of coach, possible rotation of the pillars of different plane-frames regarding to the original position around the initial centerline. The basic algorithm calculates constant torsional rigidity along the whole length of coach but there is a possibility to calculate with changing torsional stiffness of body sections along the coach length.
- This method contains the transloading opportunity of pillars. After given deformation and angle rotation the contact may transfer from the cantrail to the waistrail or to the lower side of (window)pillars. (Anyway the maximum deformations of coach were reached before the waistrail touched the ground at the real full-scale rollover tests.)

Quasi-Static Bending Tests for Calculation

At first the representative rings of the bus have to be chosen.

Collapse mode of a cross-sectional segment at quasi-static bending test and at a complete rollover test of the coach is very similar due to the low impact speed and similar loading position.

Segments to be tested are duplicated for easy deformation control and prepared on the factory's manufacturing line, so the joints of the roof-rails and side pillars or side pillars and underfloor beams are original factory-style as the used welding technology too.

Technology has a very strong influence on the stiffness of section, the collapse process depends on it. It is one of the main advantages of this method comparing with the very complicated finite element method where the technology effect can generally be approached slightly. Each segment has to be attacked by load at the cantrail with 60 degrees to the central longitudinal vertical plane of the body section. Sections to be tested are fixed under the floor-level at the plane of lowest cross-beam.

The effect of windscreen or side and rear windows can be measured too, considering the widely used glued windows.

Displacements are measured at two levels: at the cantrail and above the expectable lower plastic hinge on the side pillar. Measuring the cantrail's displacement the force magnitude and position is obtained.

The load-displacement curves are approached by twentieth-degree polynoms or spline curves. A test of duplicated front-wall unit and obtained polynome curve is shown in Fig. 9.

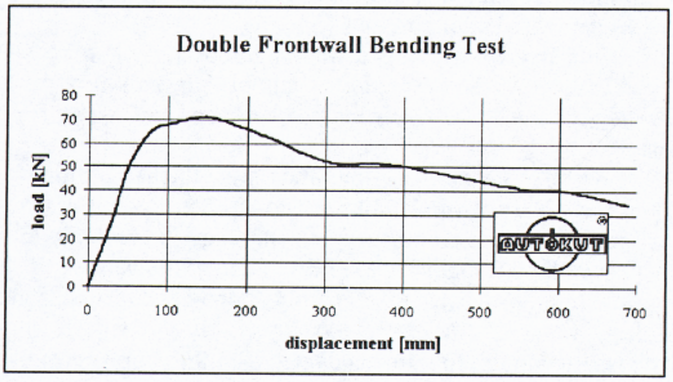
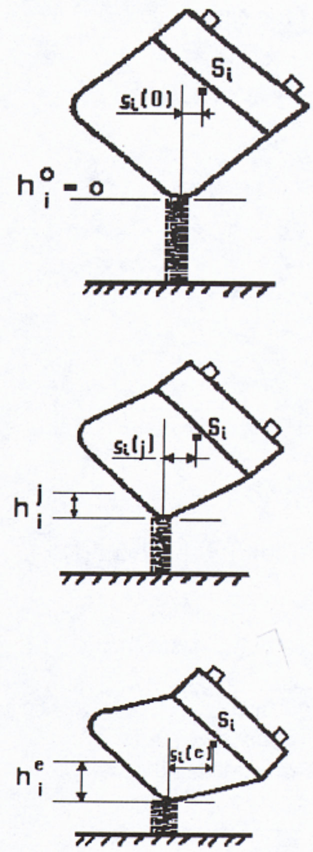


Fig. 9. Laboratory bending test for mathematical calculation of bus roof strength. Measuring the whole deformation process and the exact places of real plastic hinges the rollover simulation can be easily carried out with a simple iteration.

A 12 m long coach generally can be modeled with 7-9 pieces plane-rings linked to the chassis using the practically measured force (moment) curves of real coach rings by bending test. Having fixed the initial geometry of loading arrangement the force direction can be calculated in any internal position of deformation process by computer simulation.

Calculation Algorithm

The whole energy-absorbing process of rollover can be simulated as behavior of non-linear elastic support.
Deformation displacements of 'k' pieces of cross-section frames are modeled with 'k' pieces of non-linear springs.
(The deformations are marked two times, at the spring deformations and at the frame deformations in Figure 10.)



$$E_i^0 = 0$$

$$E_i^j = \int_0^{h_i^j} F_i(s_i, h_i)dh_i$$

$$E_i^e = \int_0^{h_i^e} F_i(s_i, h_i)dh_i$$

Fig. 10. Modeling of the deformation process as the behavior of non-linear elastic support.

symbols:

- i - serial number of frames $i = 1,2,\ldots,k$;
- k - number of plane-frames;
- j - time from the beginning of simulated rollover impact [s];
  - 0 - initial time;
  - e - total time;
- h_j^i - compression of the i^{th} non-linear spring (serial number) in the j^{th} second;

E_j^i - absorbed energy in the j^{th} second in the i^{th} non-linear spring;

s_i - horizontal displacement of center of gravity of i^{th} frame.

The calculation process is next:

a) Touching the ground these coefficients are known (or were calculated previously):

v_s^0 - velocity of center of gravity of coach;

a_s^0 - acceleration of center of gravity of coach;

ω_s^0 - angle velocity to the cross axle of center of gravity of coach;

ε_s^0 - angle acceleration to the cross axle of center of gravity of coach;
$F_i(h_i)$ - force-displacement curve obtained by quasi-static bending tests;
ϑ_0 - moment of inertia to the cross axle of center of gravity of coach;
Θ_0 - torsional rigidity of coach;
M - unladen kerb mass of coach;
E - is the total energy to be absorbed by the complete structure of the vehicle.
The duration time can be divided into dt intervals (δt= 0,001 s) and the program calculates constant forces during this interval.

b) The new motion's characteristics ($h,v_s,a_s,\omega_s,\varepsilon_s,\alpha$) can be calculated from the equations of motion, where
α - angle between initial force-effect and actual force-effect.

c) Using the $F_i(h_i)$ functions the new forces may be calculated to the connected new displacements. Taking these forces constant in a given interval the determination of new motion characteristics needs the previous step from the beginning.

d) This way the maximum deformation's length of cantrail for segment by segment can be calculated according to the required energy to be absorbed, then using the correct places of plastic hinges, obtaining from the laboratory bending tests, the exact deformation shape of the cross-sections can be easily determined comparing to the residual space.

The energy to be absorbed shall be calculated by initial potential energy of rollover situation or by appendix 1 of annex 5 to the Regulation.

CONCLUSIONS

Experience with this Regulation has some uncertainties to be cleared. The reliability and reproducibility of Type Approval tests are the most important.
The fulfillment of the full-scale test and of the whole process simulation of it requires suitable strength from the bus roof, which effectively increases the bus and coach safety.
The described numerical simulation and attached bending tests consider the whole practical collapse process of coach compartment based on factory's technology. It is more effective than a sophisticated FEM calculation, which calculates mostly with theoretically approached independent plastic hinges.
This simulation program needs obtained force (moment) curves of only 3-4 pieces of coach structural sections manufactured by factory's technology and so it makes any control test easier and cheaper.

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