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BUS ROLL-OVER SIMULATION USING COMPUTER TECHNIQUES ON THE BASIS OF MEASUREMENT RESULTS

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The purpose of this paper was to present a method whereby test results concerning the plastic deformation of a sophisticated structure were built into a simulation program which describes the whole process. The reason why test results were used was that at the present time we do not have a suitable and reliable method for the theoretical description of the plastic deformation of the investigated, statically indeterminate structure. The results calculated in accordance with the Hungarian proposal and those of crash tests were compared and the comparison proved the applicability of this method. Comparing it to the roll-over test it has a significant advantage: the application of computer simulation on the basis of laboratory tests of structural parts put together makes it possible to check the accomplishment of passive safety requirements in the early stage of design, before producing the prototype. The development and application of the method is not completed. On the one hand, improvement of the model is possible and on the other hand there is a possibility to take into consideration other roll-over test conditions by applying the method and modifying the program.

1. INTRODUCTION

As a part of the research-development activity aiming at the improvement of passive safety of buses and coaches, we have been dealing with roll-over accidents for many years [1]. The most important parts of this work are as follows: 1) to study real accidents; 2) to establish an experimental method of roll-over tests on the basis of typical accident conditions and to carry out such experiments; 3) to investigate the structural parameters of the bus in the region of plastic deformation which are required for designing and 4) to establish less expensive and less sophisticated experimental methods than crash tests.

A computer simulation program was drawn up, which proved to be capable of determining the forces loading the framework, the deformations caused by these forces and the required energy absorption during roll-over accidents. This energy absorption capacity prevents the bus superstructure from being deformed seriously or collapsed and in this way makes it possible for the occupants to survive.

These load and energy absorption parameters also served as starting points for laboratory experiments.

During the computer simulations, the deformations of both the superstructure and the soil were taken into consideration. At the same time oscillations of masses connected to the framework—for instance the axles—were disregarded. Although the theoretical approach of calculating large deformations of thin-walled tubes submitted to bending is known [2, 3], in the calculation both the deformation of the framework and the soil were taken into account with empirical equations derived from measurement results.

2. CONDITIONS CONSIDERED IN THE SIMULATION PROGRAM

Since the simulation program is not suitable for investigating the process of any accident, the considered conditions were the same as in the case of the roll-over tests: 1) the longitudinal velocity of the vehicle was disregarded; 2) it was supposed that the bus turns around a momentary axis which goes through the base points of the door-side wheels and the starting angular velocity can be neglected (in accordance with the crash test method described in the Hungarian proposal presented for the UNO ECE); 3) or after having been accelerated in lateral direction the bus collides to a low bumper, turns around the door-side wheels and crashes down upon a flat area being at a lower level, with the roof upside down (in accordance with the crash test method described in the English proposal).

The results of crash tests and tests carried out on structures proved that whenever the strength of the individual roof supporting frames are in accordance with the mass distribution of the bus—and this condition was satisfied well enough in our case—the deformation of the roof structure will be equal along the longitudinal axis of the bus. For this reason a two-dimensional model was used for the purposes of the calculation. This model consisted of a rigid body and a deformable roof supporting frame, where the mass and the inertia of the bus and the load carrying capacity of the roof structure were considered to be concentrated.

3. DEFORMATIONS OF THE BUS FRAMEWORK

As it was proved by the experimental simulation of roll-over accidents, the deformations were restricted to the upper part of the superstructure. For the description of the deformation, the model shown in Fig. 1 proved to be suitable. It means that the roof structure of the bus can be regarded as a frame consisting of roof ribs and window columns which are fixed at the lower beam of the window

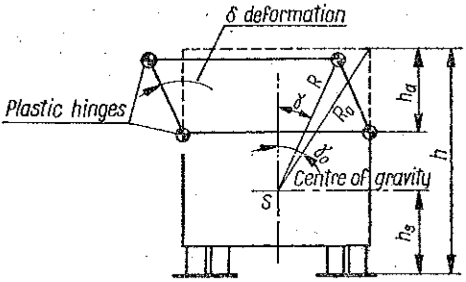

FIG. 1. Theoretical roof supporting frame for the investigation of plastic deformation.

panel. The parts of the superstructure under the lower beams of the window panels were considered to be rigid. This approximation is acceptable considering real accidents, though it does not correspond to the results published by other authors [4].

Experiments were carried out to determine the relationship between the bending moment M and the angle of rotation δ in the case of plastic hinges forming on tubes with rectangular cross-section. This relationship can be described with the empirical equation

$$M = A\delta^{B} e^{-\delta C},$$

where A, B and C are constants. The experiments were performed partly on specimens where the ratio between the outer size $\mathbf{a}$ and the wall thickness $\mathbf{v}$ varied between

$$\frac{v}{b} = 0.03 - 0.1 .$$

Experiments were carried out on full scale models developed for this particular purpose and on real bus frameworks. The relationship between the load of the inclined influence line applied along the roof edge and the angular displacement of the window column was found to be similar to the equation mentioned above. This load carrying capacity of the roof structure was concentrated to one of the four joints of that mechanism which represents it in the calculation model.

During the roll-over process the roof structure becomes deformed first in one and then in the other direction (Fig. 2). At the beginning of the first deformation

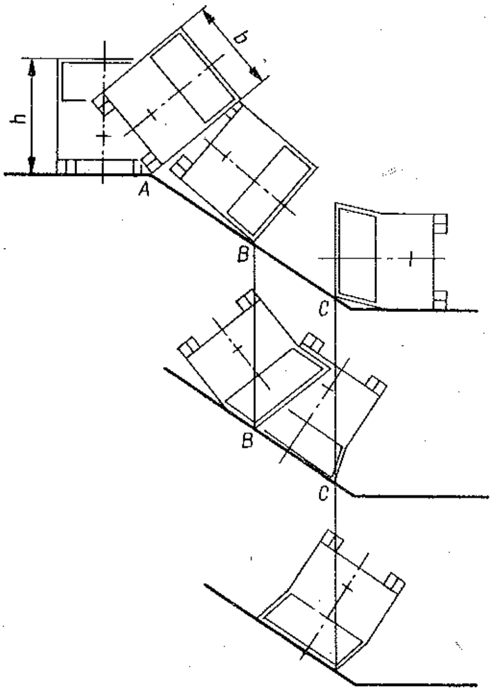

FIG. 2. Rolling process of the bus with characteristic stages of deformation.

period the structure is still unharmed, therefore the relationship between the local carrying capacity and the deformation can be characterized by a single curve, as it is shown in Fig. 3. When the structure is deformed in the opposite direction, the load carrying capacity depends on the extent of the damage of the structure, that is the deformation having occurred during the first stage. This effect was taken into account in a similar equation by a reducing factor, where this factor depends on the extent of the greatest deformation in the first phase.

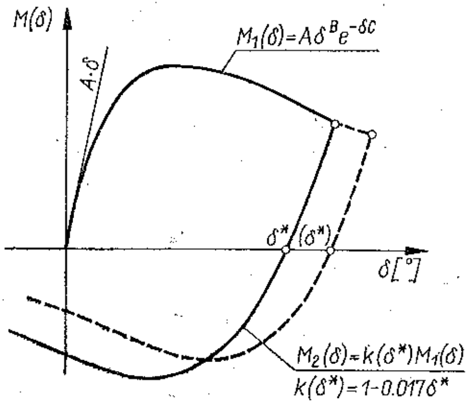

Fig. 3. Relationship between the load carrying capacity and deformation of the roof in the case of two-way deformation.

Since during real accidents and roll-over tests the structure is submitted to dynamic effects, the effect of the strain rate of plastic deformation was investigated experimentally. These experiments were performed on small-sized tubes, where the sizes were selected on the basis of the size of an actual pillar. The size of the specimens and the impact velocities were determined in such a way that the range of the local strain rate during the test would include the actual strain rate occurring in a real accident. The results of our experiments prove that an increasing strain rate gives higher hardening of the specimen than it could be expected from the results of tension-tests, but this hardening is not substantial in the tested range of strain rate. On the basis of these results the effect of strain rate was neglected in the calculations.

4. DEFORMATIONS OF THE SOIL

At the beginning the deformation of the soil was disregarded in the calculations, so the calculated load of the superstructure was too high in comparison with the results of the tests. For this reason we deemed it necessary to modify the program, so that the deformation of soil could be taken into consideration.

It was not possible to determine the deformation of the soil from its known mechanical parameters because the edge of the roof structure deforms only the upper layer of the soil, which is generally grassy and inhomogeneous.

The deformational properties of the soil were divided into two parts. Forces perpendicular to the soil were estimated by experiments. A rectangular wedge was pressed into the soil with increasing force at different angles and the $F_{x'}(s, \varphi-\delta)$ function of two variables which describes the relationship among the load $F_{x'}$ and the depth of the displacement into the soil s and the adjustment of the wedge $\varphi-\delta$.

In the description of forces parallel to the soil, it was supposed that they can be described with the

$$F_{y'}=-kv_{y'}^{n}\,s^{m}$$

equation where k, n and m are constants, $v_{y'}$ is the velocity of the roof edge when it slips in the direction of the slope and s is the same as above. The values of the constants were determined by means of a trial-and-error method, so that the simulation results would be approximately equal to the results of our crash tests concerning the soil deformation.

5. CALCULATION MODEL AND PRINCIPLE OF THE SIMULATION

For the purpose of the calculation, a model shown in Fig. 4 was created, where the bus consisted of a rigid body and a massless deformable roof structure. This model was examined in a coordinate system the origin of which was fixed to the impact point of the roof edge. Supposing a time interval Δt, from the position and the kinetic properties of the deformed bus at time t, a rigid body-like displacement was determined, which causes the edge to be penetrated into the soil. At this point of time the state of equilibrium comes to an end. The program—its simplified flowchart is shown in Fig. 5—computes the new, deformed shape, soil deformation and kinetic properties at the point of time $t+\Delta t$ by iteration. The main principle of this iteration is to restore the state of equilibium. The condition of restoring

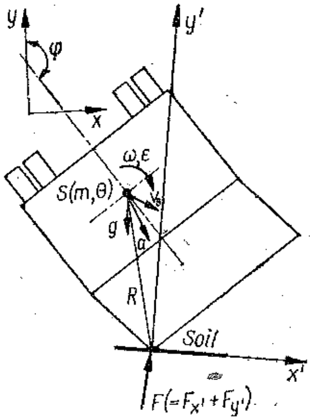

FIG. 4. The model used for the purposes of calculation.

the state of equilibrium is that the load applied to the roof-edge and to the soil should be in equilibrium and should correspond to the deformation which has occurred. As opposed to the usual way, not only the difference between two successive calculated results but the balance of energy were set up as an additional condition of accuracy, which meant the termination of the iteration. By means of this unusual condition, the accumulation of errors could be limited.

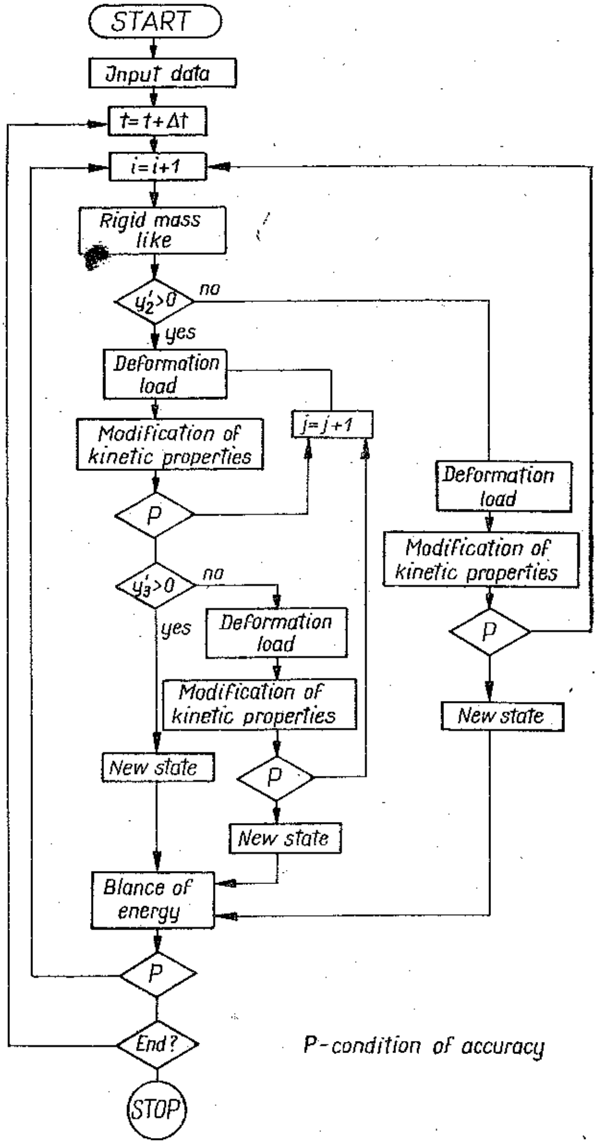

FIG. 5. Simplified flowchart of the simulation program.

6. RESULTS

The performed calculations gave the possibility of comparing and evaluating the differences caused by the modification of different parameters—e.g. load carrying capacity of the roof structure, mass of the bus, height of centre of gravity, shape—and to establish the satisfactory roof strength on the basis of the Hungarian and English proposals.

Figure 6 shows the rolling process of the bus which was used as a basis for the comparison when the strength of the roof was not satisfactory; therefore, the structure collapsed in the first stage of deformation.

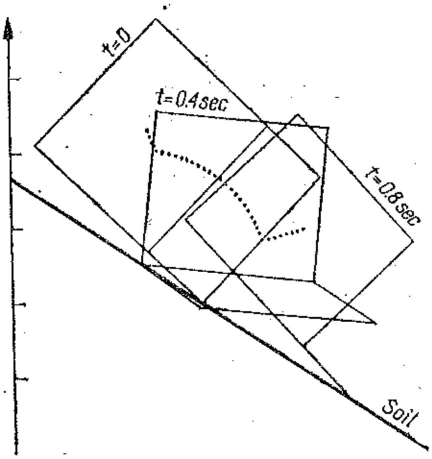

FIG. 6. Rolling process of the bus having not satisfactory roof strength (according to the Hungarian test proposal).

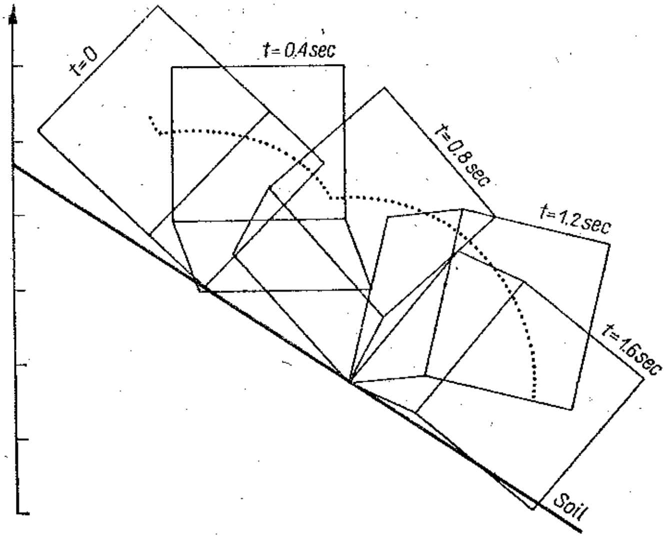

FIG. 7. Rolling process of the bus having statisfactory roof strength (according to the Hungarian test proposal).

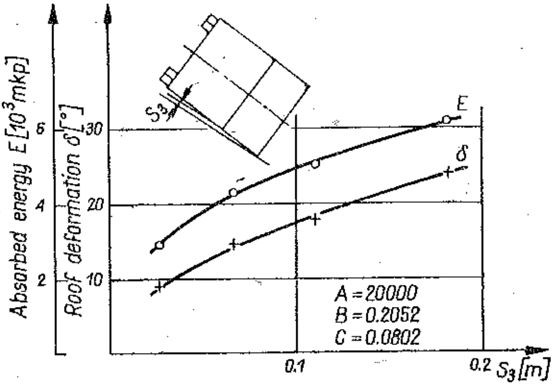

FIG. 8. Effect of side wall convexity or/and starting position on the roof deformation.

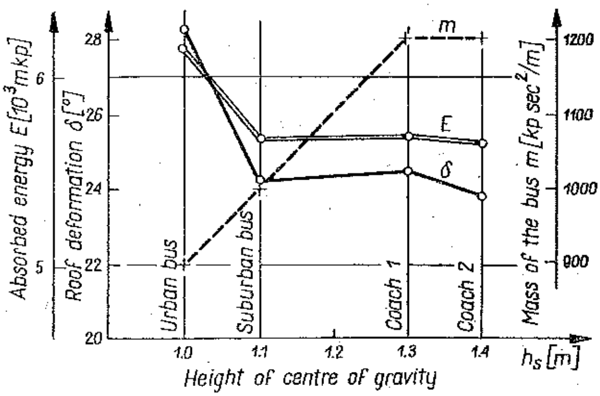

FIG. 9. Effect of the bus type on the roof deformation.

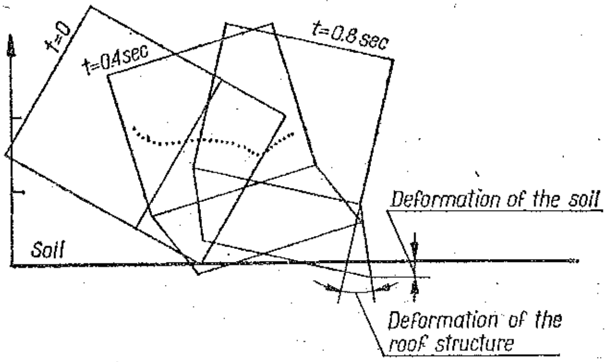

FIG. 10. Rolling process of the bus having satisfactory roof strength (according to the English test proposal).

Figure 7 shows the reinforced structure where roof deformation is limited, so the protection of the survival space was provided.

Figure 8 shows an example for analysing the Hungarian proposal. It presents the deformation (angle of rotation δ) of pillars and the energy E absorbed by the roof structure in the function of the distance S_3 between the ground and the lower beam of the window panel at the beginning of the collision. In this case the lower beam of the window panel always collides to the soil and the angular deformation of the pillars essentially depends on the distance S_3, with constant parameters and fixed starting kinetic state of the bus. With these constant conditions the distance S_3 depends only on the convexity of the side wall—or the starting angular position—of the bus.

Different types of buses and coaches corresponding to the Hungarian proposal were compared as to the angular displacement of the pillars and the energy absorbed by the roof structure. As Fig. 9 shows the mass itself does not indicate the determining factor, since with an increasing mass the load of the roof does not change proportionally; instead, the mass and the height of the centre of gravity can be regarded as determining factors. Calculations were performed with a different load carrying capacity of the roof on the basis of both the English and the Hungarian proposals. (Figure 10 shows the rolling and deformation process in the case of the test corresponding to the English proposal). Figure 11 represents the calculated highest deformation of the window columns in the function of the load carrying capacity of the roof. The range of results of the calculations performed on the basis of the English proposal is due to the uncertainty of parameters belonging to the starting position in the deformation phase. As the figure shows, the failure of the roof occurs below a critical load carrying capacity and this critical value is significantly higher in tests according to the English proposal. This fact was also proved by experiments carried out on small bus models [5].

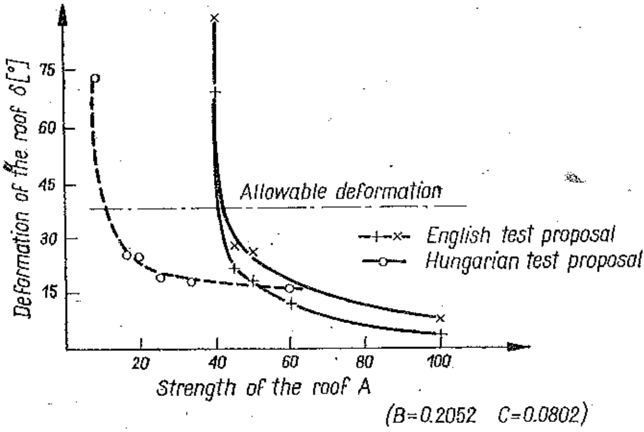

FIG. 11. Roof deformation in the function of roof strength.

The results mentioned above concern the first stage of roof deformation only because it proved to be a determining factor in the point of crash test results.

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STRESZCZENIE

NUMERYCZNA SYMULACJA WYWROTKI AUTOBUSU NA PODSTAWIE WYNIKÓW POMIARÓW

Celem pracy jest opracowanie metody pozwalającej na wykorzystanie wyników pomiarów dotyczących plastycznych deformacji elementów nadwozia autobusu do programu numerycznego symulacji procesu wywrotki autobusu. Jest to jedyna w obecnej chwili droga postępowania ze względu na brak wiarygodnej metody teoretycznego opisu deformacji struktury nadwozia w zakresie plastycznym. Wyniki obliczeń wykazały zgodność z doświadczeniami dotyczącymi zgniatania nadwozi. W stosunku do badań doświadczalnych program symulacji zderzeń posiada niewątpliwą zaletę pozwalającą wprowadzić i sprawdzić przydatność niektórych elementów bezpiecznego nadwozia zanim jeszcze zbudowany zostanie prototyp.

Резюме

ЧИСЛЕННАЯ ИМИТАЦИЯ ОПРОКИДЫВАНИЯ АВТОБУСА НА ОСНОВЕ РЕЗУЛЬТАТОВ ИЗМЕРЕНИЙ

Целью работы является разработка метода, позволяющего использовать результаты измерений касающихся пластических деформаций элементов кузова автобуса для программы численной имитации процесса опрокидывания автобуса. Это единственный в настоящий момент путь поступания из-за отсутствия достоверного метода теоретического описания деформации структуры кузова в пластической области. Результаты расчетов показали совпадение с экспериментами касающимися сдавления кузовов. По отношению к экспериментальным исследованиям программа имитации столкновений обладает несомненным достоинством позволяющим ввести и проверить пригодность некоторых элементов безопасного кузова прежде чем еще будет построен прототип.

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