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# Analysis of the Superstructure of a Designed Bus in Accordance with Regulations ECE R 66

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**ABSTRACT**

Compliance with certain technical standards and requirements in designing and producing vehicles is necessary for vehicle manufacturers. Within this scope, Regulation ECE R 66 – Large Passenger Vehicles - The Strength of the Superstructures – was studied in this investigation regarding the "Motor Vehicles Type Approval Directive". A finite element model of the superstructure of a designed bus was created and analysed according to ECE R 66 requirements and the results were compared with the test results of a section of the bus superstructure.

**Key Words**: *Bus, Superstructure, Roll-over test, ECE R 66 Regulations, Finite element analysis*

## 1. INTRODUCTION

In this study, a section of the superstructure of a designed bus was modelled with the software CATIA by means of investigating the Regulation ECE R 66 concerning the superstructure strength of passenger transportation vehicles. The model was analyzed using the finite element method. In solution, the displacements and the deformations at the joints were examined and the results were compared with those of the roll-over test performed according to the conditions of the regulations [1, 2].

Despite the fact that intensive investigations are carried out on this subject, due to commercial competition and consequent secrecy, few papers are available. Abe et al [3] simulated the three-dimensional behaviour of two vehicles at collision using dynamic models numerically and compared the calculated results with real vehicles' collision test data in their study.

Takubo and Mizuno [4] analyzed sport utility vessel (SUV) accidents using statistics and the case study method accessing a national accident database and detailed accident investigative data. Among the case studies, one rollover accident was analyzed.

The study of Parenteau et al [5] was to estimate the distribution of rollover accidents occurring in the field and to compare the vehicle kinematics in the predominant field crash modes with available laboratory tests. For this purpose, the authors analyzed US accident data to identify types and circumstances of accidents for vehicle rollovers.

Eger and Kiencke [6] investigated the influence of various parameters and their variations on rollover accidents in their study in order to show that even simple models could deliver important properties of vehicle rollover.

Dias and et al in [7] present a new method for predicting the rollover limit of buses, based on a theoretical model and dynamics test. These tests performed on the road under real conditions and the developed mathematical model should be able to predict a reliable rollover limit of a bus.

Castejon and et al [8] exhibit a developed simulation technique for the rollover test of buses, which is applied to a new concept of lightweight bus wholly made of composites. After the rollover simulations based on this developed technique are applied to the composite bus, a prototype of the bus was built and tested.

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Hoskins and El-Gindy in [9] perform a simulation of an FMVSS 208 rollover dolly test of a generic pickup truck model. They use data from published real-world rollover dolly tests of large passenger cars to validate the simulations, and the pickup truck model having properties similar to that of the cars used by other researchers in their rollover tests. The vehicle dynamic responses during the rollovers and the simulation were analyzed and compared with each other.

Renfroe and et al [10] develop a simple technique to evaluate the limits of the roll characteristics of a vehicle. The analysis enables quantification of the effects of springs, dampers, roll centre location, masses and centre of gravity locations on the propensity to roll under the on-road manoeuvre conditions.

Dahlberg and Stensson in [11] present a method to determine dynamic rollover threshold of heavy trucks and apply a parameter sensivity study. They investigate the influences on the steady-state rollover threshold and dynamic rollover threshold from roll stiffnesses and roll centre heights.

Koppel and et al [12] aim in their study to determine, how important vehicle safety is in the new vehicle purchase process. They find out that the consumers recently rank safety-related factors (e.g. EuroNCAP safety ratings, advanced breaking systems, front passenger airbags, etc) as more important than non-safety-related features such as price, reliability, navigation systems etc.

Kwasniewski and et al in [13] describe an assessment program for paratransit buses concerning their crashworthiness and safety of passengers. They use the nonlinear explicit dynamic code LS-DYNA to demonstrate a numerical approach for a bus structure approval.

## 2. NECESSITY OF TECHNICAL REGULATIONS IN AUTOMOTIVE INDUSTRY

In the automotive industry, technical regulations are needed because of the reasons below:

- For providing life safety and reducing accidents.
- For providing international cooperation for determining the minimum technical conditions in systems and parts of vehicles.
- Because of rapidly increasing traffic density with the increase in the number of vehicles produced.

Hence compliance with technical standards and requirements in designing and producing vehicles is necessary for vehicle manufacturers. Additionally traffic laws of developed countries require that vehicles manufactured must be in conformity with the structure of main roads and traffic safety from the point of view of vehicle production and usage. During the production stage of vehicles, corresponding ministries of the countries are authorized to legislate for Motor Vehicle Type Approval Directives and other Regulations connected with these Directives.

These regulations contain control processes consisting of testing motor vehicle types or systems and parts of these vehicles with certain methods and involve procedures of documentation of the results' appropriateness to the technical regulations. Vehicles can only be manufactured after this process called "type approval". Traffic registration of a vehicle cannot be performed before the type approval has been issued. In this study, the analyses necessary for obtaining the type approval for a new bus type whose manufacture is planned, were performed.

## 3. BUS PRODUCTION AND REGULATION APPLICATIONS TO BUSSES

### 3.1. Bus Production

According to Motor Vehicle Type Approval Regulations, a bus is a vehicle with an engine, which has more than 8 seats excluding its driver, transports passengers and whose laden mass exceeds five tons. It is possible to classify bus production into two groups. These are:

- Chassis and body produced separately as two parts (chassis and body)
- Chassis and body produced together as one part (monocoque chassis-body)

#### 3.1.1. Separately produced chassis and body

Chassis structures of busses are the rectangular-like structures that are constructed by joining two parallel main beams with the gap elements as seen in Figure 1. They bear the whole body and loads of passengers that amount to an average of 71 kg per person. This type of structure has the special name "chassis", on which the motor and transmission systems are assembled, and it possesses moving capability like a vehicle, without having any superstructure (carcass system) as given in Figure 2.

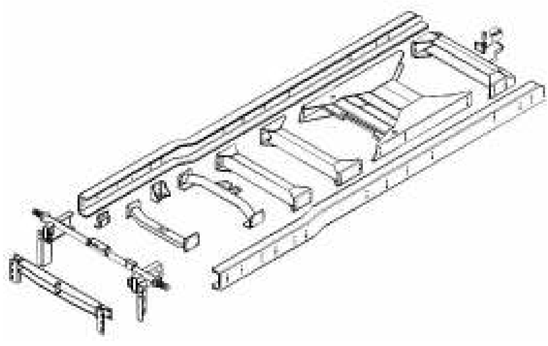

Figure 1. Assembling chassis [14, 15].

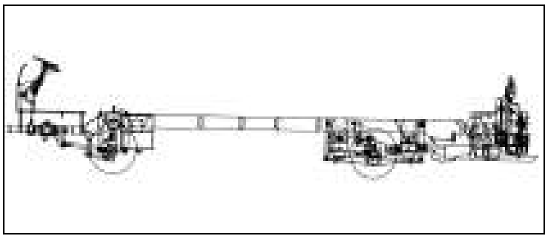

Figure 2. Drive-train assembled on chassis.

The superstructure of a bus consists of pillars and a metal sheet covering which forms a “closed safe volume”. Additionally, the body contains components such as doors, windows, air-conditioning systems and emergency exits within its structure. Figure 3 shows a bus superstructure to be assembled on the chassis. The main elements of this system consist of main beams named “pillars”, strength increasing interior beams and reinforcement bars which all together form doors, windows etc. and carry the whole structure and static as well as dynamic loads.

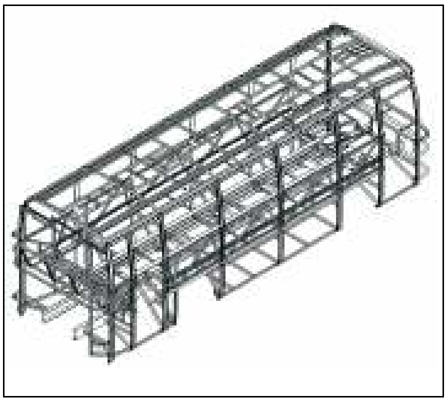

Figure 3. Superstructure of the designed bus [16].

### 3.1.2. Monocoque chassis and body

The floor carcass both functions as a chassis and bears the passenger platform. Hence the monocoque chassis and body complete each other to form a vehicle, and this type of chassis cannot move independently. The fact that there is no separate chassis lightens the vehicle mass. Generally this structure is preferred for vehicles with air suspension and for busses whose floor is required to be closer to the ground. This means a drop in the gravity center of the bus, which improves the vehicle stability substantially.

## 4. ROLL-OVER TEST ACCORDING TO ECE R 66

### 4.1. Aim of the Test in the Regulation

Nowadays, the safety against roll-over of vehicles transporting passengers is very important. In the world, this subject is under the control of formal sanction associations such as the EC (European Community), ECE (Economic Commission for Europe) and FMVSS (Federal Motor Vehicle Safety Standards).

Due to the abundance of limits enacted by these associations for the provision of sufficient life safety during vehicle roll-overs and crashes, at the design stages computer simulations of vehicle accidents have been very important. The main aim of Regulation ECE R 66 is to design and produce bus superstructures satisfying the requirement that passengers and driver in the passenger department must remain alive in the standard roll-over conditions defined in the Regulations. The Regulation therefore defines a “residual space” as given in Figure 4 [1, 2]. If this residual space, represented here by a trapezoid that is placed in the passenger department within the bus cross-section to be tested, is not damaged during and after the test, it means that this bus structure has been designed and manufactured in a way which significantly minimizes the injury risk of passengers and driver during an accident.

### 4.2. Characteristics of the Bus

The characteristic dimensions and weight distributions of the designed unladen bus are determined in the design stage as follows:

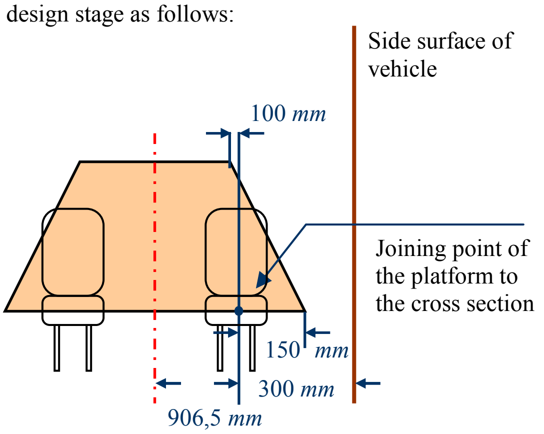


Figure 4. Dimensions of the platform of the residual space [16].

**Distributions of weights of unladen bus**

| | | | |
|---|---|---|---|
| $M_g$ | = | 9170 *kg* | Unladen kerb mass of the vehicle |
| $M_f$ | = | 2770 *kg* | Weight of front axle |
| $M_r$ | = | 6400 *kg* | Weight of rear axle |
| $M_L$ | = | 4470 *kg* | Weight of left side of vehicle |
| $M_R$ | = | 4700 *kg* | Weight of right side of vehicle |

**Dimensions of the bus**

| | | | |
|---|---|---|---|
| L | = | 4160 *mm* | Span width of axle |
| FT | = | 1866 *mm* | Width between the front tire centers |
| $r_{dyn}$ | = | 409 *mm* | Diameter of the tire for 245/70 R 19.5 |
| W | = | 2355 *mm* | Overall width of the vehicle |
| H | = | 3350 *mm* | Height of the vehicle |

**Center of the gravity of the bus**

| | | | |
|---|---|---|---|
| $l_F$ | = | 4909 *mm* | Distance of the front of the vehicle from the centre of gravity of the vehicle |
| $l_R$ | = | 3921 *mm* | Distance of the rear of the vehicle from the centre of gravity of the vehicle |

| | | | |
|---|---|---|---|
| t | = | 234 *mm* | Distance between gravity center of the vehicle and longitudinal section center plane ABOD as given in Figure 5 and 6 (Determined as in Table 1) |
| a | = | 2904 *mm* | Distance of gravity center of the vehicle from the front axle (Determined as in Table 1 and Figure 6) |
| b | = | 1256 *mm* | Distance of gravity center of the vehicle from the rear axle (Determined as in Table 1 and Figure 6) |
| $H_S$ | = | 1036 *mm* | Averaged height of the centre of gravity of the unladen vehicle (Determined and shown as in Table 1 and in Figure 6) |
| $h_f+h_f'$ | = | 83 *mm* | Fall of the centre of gravity (Graphically determined and measured as in Figure 7) |

The position of the centre of gravity of the bus was calculated in Table 1 and HS was determined to be 1036 mm.

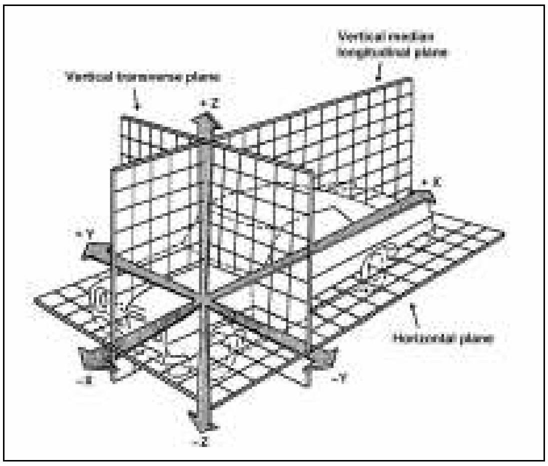


Figure 5. Vertical transverse and median longitudinal plane according to ECE R 29 [2].

### 4.3. Selection of the Superstructure Section

For the roll-over test, a section of the bus superstructure was selected that was situated between two similar pillars and possessed reinforcement elements and complete windows on both sides as given in Figure 8. In the selected section, weights representing sheet metal plates, window panes, bars for ceiling baggage, seat rails and seats were placed at their original positions in the passenger compartment. By means of all the weights and their distributions, the vertical position of the gravity center of the section to be tested, was accommodated close to that of the whole vehicle's center of gravity. The mass of the section is 746 kg and it amounts to 8.14 % of the whole mass of the bus.

### 4.4. Preparation of the "Residual Space" Platform

For the preparation of the “residual space” platform to be placed in the superstructure section that will be tested, the distance between the axes of the two exterior passenger seats in the bus is used as given in Figure 4 and explained in Reference [1, 2]. So, in the designed bus, the distance between the axes of the two exterior passenger seats was measured as 1813 mm. Figure 4 exhibits dimensions of the residual space platform which were determined by using the following distances.

- Lower edge length of the trapezoid: 2 (906.5+150) = 2113 mm
- Upper edge length of the trapezoid: 2 (906.5-100) = 1613mm
- Height of the trapezoid: hT = 750 mm ( Given in ECE R 66)

### 4.5. Roll-over Test

The roll-over test and its execution are explained explicitly in Reference [1, 2]. The course of the roll-over test performed on the section representing the whole superstructure of the designed bus, which was produced for experimental research by BMC Industry and Trade Inc., is shown in Figure 7 and 9 [14]. After the roll-over test, it was determined that no deformation occurred in the residual space platform representing the area of the passenger department. This means that the section and/or superstructure of the bus were designed properly according to the Regulations ECE R 66.

Table 1. Determination of the location of gravity center of the bus.

| **Section** | **Static moment (kgm)** | **Distance (mm)** | **Explanation** |
|---|---|---|---|
| Longitudinal-section | $M_L \cdot x = M_R \cdot (FT - x)$ | $x = 956.40$<br>$t \cong 23.4$ | Figure 6 |
| Cross-section | $M_r \cdot (L - a) = M_f \cdot a$ | $a \cong 2903.4$<br>$b \cong 1256.62$ | Figure 6 |
| Forces acting on bus with $\alpha = 2.9°$ | $M_g \cdot (a + \Delta a) \cdot \cos\alpha =$<br>$(M_r + \Delta M) \cdot L \cdot \cos\alpha$<br>$for \ldots \alpha = 2.9°$<br>$H_S = \frac{L \cdot \Delta M}{M_g \cdot \tan\alpha}$ | $H_S = 1036$ | Averaged height of the centre of gravity of the unladen vehicle<br>Figure 6 |
| Auxiliary Calculations | $\Delta a = \frac{(M_r + \Delta M) \cdot L}{M_g} - a$ (*)<br>$a = \frac{M_r}{M_g} \cdot L$ (**)<br>Eq. (**) is put into Eq. (*)<br>$\Delta a = \frac{\Delta M}{M_g} \cdot L \Rightarrow$<br>$\tan\alpha = \frac{\Delta a}{H_S} \Rightarrow H_S = \frac{L \cdot \Delta M}{M_g \cdot \tan\alpha}$ | | Figure 6 |

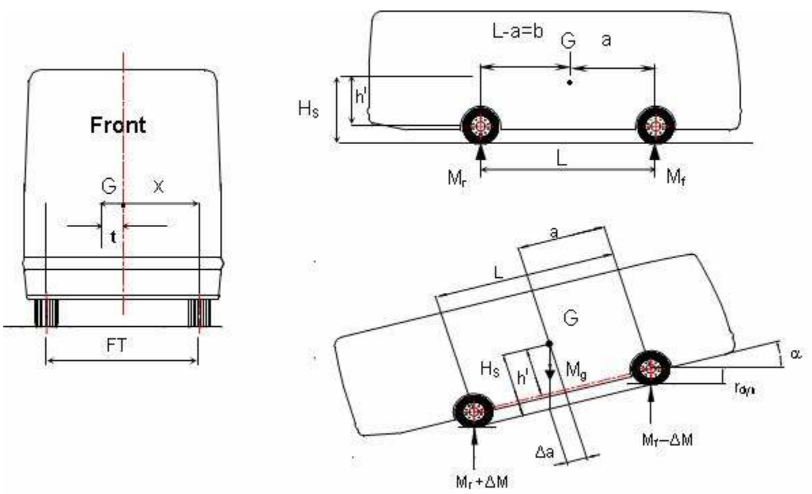


Figure 6. Characteristic distances in transverse and longitudinal bus section as well as forces acting on bus in angle of α [16].

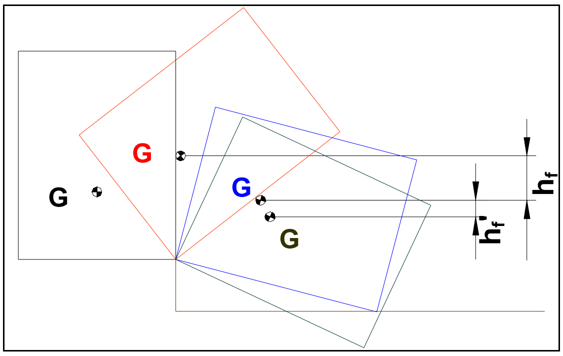

Figure 7. Course of centre of gravity of the designed bus section during the roll-over test [16].

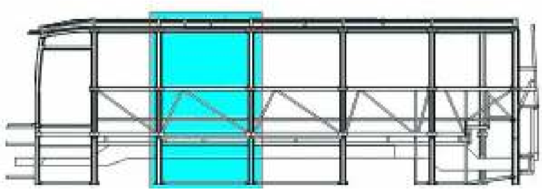
Figure 8. Selected carcass section – Model of BMC bus [16].

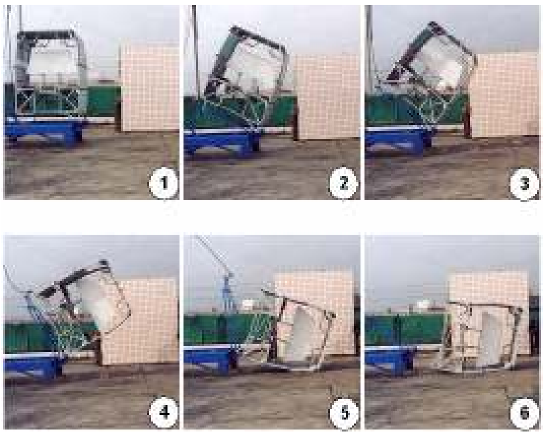

Figure 9. Roll-over test [16].

## 5. STRUCTURAL ANALYSIS

### 5.1. Analysis of the Superstructure of the Bus by Energy Absorption Method

Energy absorption of the bus superstructure in a roll-over test can be determined in accordance with Regulations ECE R 66 as follows and assumptions of the regulations listed below apply also to this analysis:

- Body structure of the bus is a rectangle.
- The hanger system is joined rigidly.
- The motion of the bus section is just a roll motion of a rigid body.

The total energy to be absorbed in a roll-over test can be determined by equation (1a) or (1b):

$$E^* = 0.75Mg\left(\sqrt{\left(\frac{W}{2}\right)^2 + H_S^2} - \frac{W}{2H}\sqrt{H^2 - 0.8^2} + 0.8\frac{H_S}{H}\right) \text{[Nm](1a)}$$

$$E^* = 0.75Mg\left(h_f + h'_f\right) \quad \text{[Nm]} \quad \ldots(1b)$$

Putting all values given above into Eq. (1a) delivers the total energy to be absorbed by the superstructure of the designed bus in a possible roll-over accident.

$$E^* = 0.75 \cdot 9170 \cdot 9.81\left(\sqrt{\left(\frac{2.355}{2}\right)^2 + 1.036^2} - \frac{2.355}{2 \cdot 3.35}\sqrt{3.35^2 - 0.8^2} + 0.8\frac{1.036}{3.35}\right)$$

$$E^* = 45370\,Nm = 45.4\,kJ$$

The main bearers forming the vehicle's body should be a complete ring circle. These closed rings increase strength of the bus superstructure about 30% more than the main bearers consisting of open rings (Figure 8 and 10). The superstructure of the designed bus to be analyzed consists of eight closed rings that are accommodated from the front to back of the bus, and the rings from the front to the gravity center of the bus are called "front rings", while those from the gravity center to the back of the bus are called "back rings".

The superstructure-section of the bus to be tested is abutted on the third (F3) and the fourth (F4) frame bearer, which has the number 3 as given in Figure 10. At the end of the roll-over test, the resulting fall of the center of gravity ($h_f + h'_f$) of the superstructure-section was measured and graphically found out to be about 83 cm. By means of this value, the energy absorbed by the section rolled-over in the test is determined by Eq. (2) as $E_3$ = 6.08 kJ.

$$E_3 = mg(h_f + h'_f) \quad (2)$$

$$E_3 = 746 \cdot 9.81(0.58 + 0.25)/1000 = 6.08 \text{ kJ}$$

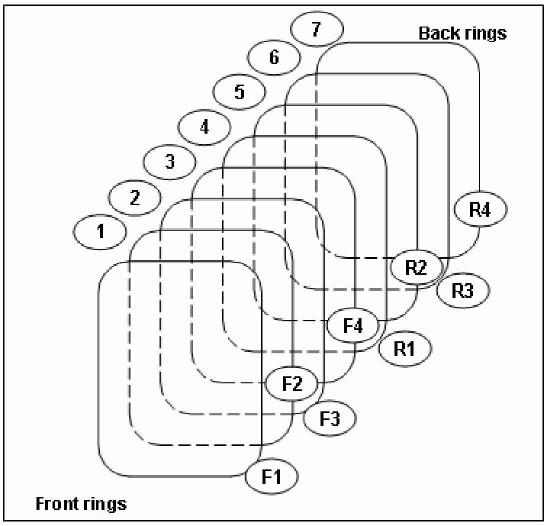

Figure 10. Representative closed rings of the bus superstructure [16].

### 5.2. Analysis of the Bus Superstructure using FEM and Results

The model of the superstructure of the designed bus was prepared in CATIA software. In order to decrease the CPU-time in analyses, any parts of the superstructure that are irrelevant for the stiffness of the section were neglected. In addition, the test section possesses some auxiliary elements for execution of the test, which do not contribute to its stiffness. The floor carcass functioning as a chassis and body was modelled and the chassis and body were meshed with "Solid elements" and "Shell 63 elements", respectively, and then the file was transferred into ANSYS software (Figure 11) [17, 18]. In analysis it was assumed that elastic deformations are negligibly small. Deformations obtained in analysis, which occurred in all rings of the modelled bus after roll-over simulation, were determined as follows:

| **Rings** | **Front side** | **Rings** | **Rear side** |
|---|---|---|---|
| 1F | $d_1$=0.70488 *m* | 1R | $d_5$=0.93406 *m* |
| 2F | $d_2$=0.68665 *m* | 2R | $d_6$=1.00533 *m* |
| 3F | $d_3$=0.74543 *m* | 3R | $d_7$=1.04984 *m* |
| 4F | $d_4$=0.83854 *m* | -- | ------------ |

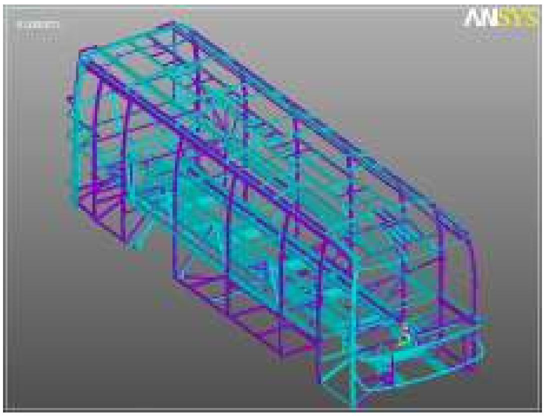

Figure 11. Model of the designed bus superstructure without sheet metal.

The absorption energy obtained from the analysis was calculated as:

$$E_3 = mgd_3 = 746 \cdot 9.81 \cdot 0.7455 / 1000 = 5.46 \text{ kJ}$$

By means of the displacement amounts obtained from the analysis as mentioned above and as seen in Figure 12-13, the energy that would be absorbed by all superstructure-sections was determined as in Table 2:

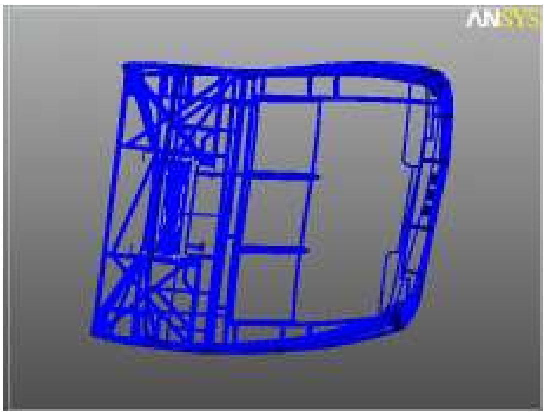

Figure 12. Analysis of the model under loading.

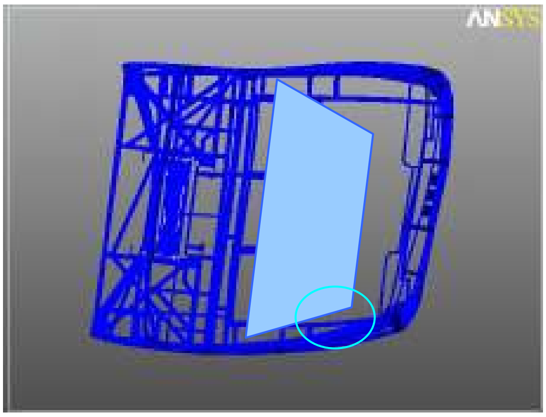

Figure 13. "Residual space" after roll-over test.

Table 2. Energy that would be absorbed by all superstructure-sections.

| **Front side** | **Rear side** |
|---|---|
| $E_1 = E_3\,(d_1/d_3)$= 5.75 kJ | $E_5 = E_3\,(d_5/d_3)$ = 7.62 kJ |
| $E_2 = E_3\,(d_2/d_3)$= 5.60 kJ | $E_6 = E_3\,(d_6/d_3)$ = 8.20 kJ |
| $E_3 = E_3\,(d_3/d_3)$= 5.46 kJ<br>Result of the analysis<br>**$E_3$ =6.08 kJ**<br>**Result of the test** | $E_7 = E_3\,(d_7/d_3)$ = 8.563 kJ |
| $E_4 = E_3\,(d_4/d_3)$ = 6.84 kJ | ----- |
| $E_{F,Total}$ = 24.27 kJ | $E_{R,\,Total}$ = 24.383 kJ |
| $E_{Total} = \Sigma\, E_{Fi} + \Sigma\, E_{Ri}$ = 48.653 kJ | |

It can be concluded that the results of the test and analysis for section E3 are very close. The energies to be absorbed by the other sections were calculated by means of the reliable value of section E3. The distance of all main bearers to the gravity center of the bus (l) was determined as follows:

| **Front side** | **Rear side** |
|---|---|
| $l_{F1} = 4.30\ m$ | $l_{R1} = 0.71\ m$ |
| $l_{F2} = 3.40\ m$ | $l_{R2} = 2.18\ m$ |
| $l_{F3} = 2.33\ m$ | $l_{R3} = 3.55\ m$ |
| $l_{F4} = 0.80\ m$ | ------------ |
| $\Sigma E_{Fi} \cdot l_{Fi} = 63.4$ kJ | $\Sigma E_{Ri} \cdot l_{Ri} = 53.69$ kJ |

Averaged distances of the main bearers accommodated at the front and at the rear of the gravity center of the bus can be determined by equations (3).

$$L_F = \frac{\sum_{i=1}^{i=n} (E_{Fi} l_{Fi})}{\sum_{i=1}^{i=n} E_{Fi}} \qquad L_R = \frac{\sum_{i=1}^{i=p} (E_{Ri} l_{Ri})}{\sum_{i=1}^{i=p} E_{Ri}} \qquad (3)$$

LF=63.40÷24.27=2.61 m LR=53.69÷24.383=2.20 m

If all obtained values are assessed as given in Table 3, it results that the energy absorbed in all superstructure-sections is 7-36 % higher than the required values and thus the superstructure of the designed bus fulfils the Regulation conditions. Moreover the calculated values $L_F$ and $L_R$ are sufficient.

Table 3. Evaluation of the obtained results.

| ***Conditions*** | ***Determined values*** | ***Result*** |
|---|---|---|
| $E_{Total} \geq E^*$ | 48.653*kJ*>45.40*kJ* | Suitable for Regulation |
| $E_{F,Total} \geq 0.4\ E^*$ | 24.27 *kJ*>18.16 *kJ* | Suitable for Regulation |
| $E_{R,Total} \geq 0.4\ E^*$ | 24.383 *kJ*>18.16 *kJ* | Suitable for Regulation |
| $L_F \geq 0.4\ l_F$ | 2.61 *m*>1.96 *m* | Suitable for Regulation |
| $L_R \geq 0.4\ l_R$ | 2.20 *m*>1.57 *m* | Suitable for Regulation |

## 6. RESULTS AND CONCLUSION

In this study, the roll-over test of the superstructure-section of a designed bus was performed according to Regulation ECE R66 and the approximate values of the displacements at the main bearers were obtained (Figure 14). Further, with these values the energy absorbed by main bearers was calculated. Additionally, the modelled superstructure of the bus was analyzed so that the energy all bus sections would absorb was determined (with the help of the section test results). By means of the results obtained, it is concluded that the results of the roll-over test of the bus superstructure-section can be approached by finite element analyses. Important parameters in the design stage primarily arose from:

- Vehicle characteristics, especially the position of the gravity center of the whole bus and superstructure-section.
- The displacements in main bearers
- The total energy that the closed rings of the superstructure-section absorb.

It resulted that the residual space platform was damaged neither according to the calculations as well as the roll-over test performed with respect to Regulation ECE R66 nor in the finite element analyses. In other words, it was succeeded in proving the safety of the designed bus in the roll-over test. So it was concluded that the superstructure of the bus is a successful design that can protect the passengers and drivers during a possible accident and following roll-over.

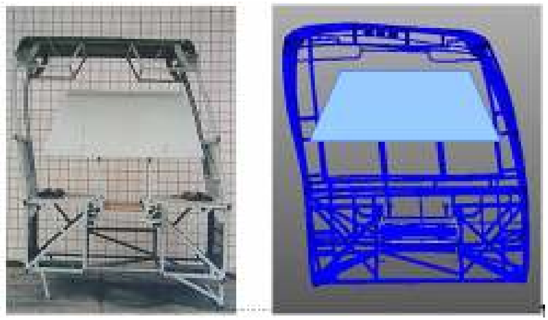

Figure 14. Comparison of the test results to the one of the FEA.

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| **Nomenclature / Abbreviations** | |
|---|---|
| EC | European Community |
| ECE | Economic Commission for Europe |
| FMVSS | Federal Motor Vehicle Safety Standards |
| MVTAD | Motor Vehicles Type Approval Directive |
| ISO | International Standard Organisation |
| CAD / CAM | Computer Aided Design / Computer Aided Manufacturing |
| FEM / FEA | Finite Element Method / Finite Element Analysis |
| M | Unladen kerb mass of the vehicle (kg) |
| g | Acceleration due to gravity ($m/s^2$) |
| W | The overall width of the vehicle (m) |
| $H_s$ | The height of the centre of gravity of the unladen vehicle (m) |
| H | The height of the vehicle (m) |
| $l_F$ | Distance of the front of the vehicle from centre of gravity of the vehicle (m) |
| $l_R$ | Distance of the rear of the vehicle from centre of gravity of the vehicle (m) |
| E* | Total energy to be absorbed (kJ) |
| $L_{F,R}$ | Weighted average distance of the declared pillars to the front / rear of the centre of gravity of the vehicle (m) |
| $l_{Fi}$ | Distance from the centre of gravity of the $i^{th}$ pillar forward the centre of gravity of the vehicle |
| $l_{Ri}$ | Distance from the centre of gravity of the $i^{th}$ pillar rearward the centre of gravity of the vehicle |