TECHNICAL QUESTIONS OF BUS SAFETY BUMPERS

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ABSTRACT

This paper is based on accident statistics, theoretical considerations and physical tests of safety bumpers and their components. The statistical analysis shows the typical bus frontal collisions, their frequency and the possible advantage of the safety bumper in the typical collisions. The theoretical considerations try to outline the possible requirements of a safety bumper: deformation capability, energy absorption capability, strength requirements relating to the bus structure behind the safety bumper system, compatibility requirements, etc. When specifying these requirements all bus categories, all kind of buses (low floor and high decker, small and large, etc.) should be considered together with their special features. There are well-defined theoretical connections between the length of the deformation, the energy absorption of the bumper and the average deceleration of the bus having safety bumper in a frontal collision. This deceleration is an important figure when regulating safety belts and seat strength in buses. The tests, the results of which are discussed in the paper include: pendulum impact tests of components of safety bumper systems, static loading tests of these components and full scale frontal impact tests with complete buses against concrete wall. The differences between the results of static and dynamic tests – carried out on the same components – are shown and discussed. It is emphasized that the bumper cannot solve all the safety problems belonging to frontal collision of buses, but it may be a useful, effective tool in some cases (avoiding underrun type accidents, reducing the decelerations below a certain impact speed, etc.)

1. INTRODUCTION

Analysing bus accident statistics collected from different sources, different countries [1] in which somebody has been injured (bus occupants or other road user), some interesting figures may be cited:

- 30-50% of the accidents happened with vulnerable partners (pedestrian, bicyclist, motorcyclist, moped, etc.) No danger for the bus occupants.
- 30-50% with cars and vans, which are weaker than the bus but not, so defenceless as above. Danger mainly for the bus driver (and crew, if any) among the bus occupants.
- 10-30% with heavy vehicles and stable objects, which are very dangerous for the bus occupants.

The very wide range scatters are due to the different countries, different traffic circumstances, different data collecting methods, different systems in statistics, etc. The frontal collisions or run over type accidents among the total bus accidents are in the range of 55-65%.

Thinking about the front safety bumper of buses, the first question to be decided is: who or what should be protected by this bumper? The bus occupants (driver, crew, passengers) or the other road users (pedestrians, bicyclist, car occupants, etc.) or the important control systems of the bus (steering, brake, electric) or to reduce the damage (cost) of the bus and/or the other vehicles being involved in frontal collision of the bus. The theoretical answer on this question is that a multifunctional safety bumper would be the optimal solution.

Formerly (in the '70-s and '80-s) the bumpers of the buses were separate units on the front wall. They did not have any special safety function; they could not protect the front wall (or anything else) even in the case of a slight frontal impact, as it is shown on Figure 1.

Figure 1. Old style bus bumper as a separate unit

In the last fifteen years the separate bumpers disappeared and the bus bumper became an integrated part of the front wall having only aesthetic function. The background of this change is basically technological, today the whole front wall is made from fibreglass reinforced plastic as a complete unit. The bumper does not have any projection from the front wall, therefore it does not have any deformation capability without damaging the front wall. Example is given on Figure 2. This practice is generally used for all kind of buses (city bus, long-distance coach, etc.)

Figure 2. Integrated bumper, part of the front wall

Figure 3. Presumably safety bumper on buses.

On the other hand, there are a few buses, running in the everyday service presumed equipped with safety bumper. Figure 3. shows an example. The criteria of these safety bumpers – on the basis of which they were designed – are not known, only their position, shape and construction give us the feeling that they could have safety function, too. The lack of an international regulation results that there are no unified, clear requirements for bus safety bumpers, which means that the possible goals of these bumpers are not cleared up yet.

2. SAFETY BUMPER CONCEPTS

There are two major lines, on the basis of which the concept of the safety bumper can be formulated. Of course these two different concepts (their components) may be combined in the future practice, but theoretically it is better to discuss them separately.

2.1. Protecting the vulnerable road users, partners in a collision

In spite of the general considerations (full frontal impact) in this case the local properties and behaviour of the bumper have special importance. Three kind of vulnerable partners could be considered:

- Pedestrians. No energy absorption, no deformations, only the surface properties of the bumper are interesting (shape, radius of edges, surface hardness) and maybe its position (height above the road)
- Cyclists, motorcyclists. The bus bumper cannot protect essentially these road users. The bus itself – whether has a safety bumper or not – is a very aggressive „partner" for them.

Figure 4. Underrun type frontal collision

- Cars, small vans. One problem is to avoid the underrun type collisions with the safety bumper. Figure 4. gives an example: the underrun type collision with a small car (Trabant) was not too severe for the bus, but it was fatal for the car. The underrun type accident raises an other problem: the damage of the vital control systems located under the driver compartment (brake, steering, electric-electronic systems) The damage of these systems means that the driver can not control the further motion of the bus, even if the first collision with the car was not too severe, the second collision could be fatal.

An other question to be considered is the energy conditions of the bus-car frontal collision. Figure 5. shows the relations, how to estimate the equivalent energies and impact speeds in two cases:

- The bus hits a rigid wall
- A car hits the bus

The symbols are: **M** = mass of the bus; **m** = mass of a car; **c** = energy dissipation factor showing the energy absorbed by anything else expect the safety bumper.

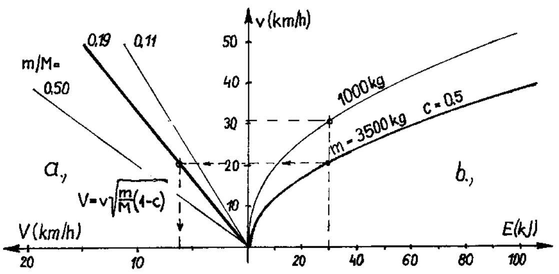

Figure 5. Equivalent impact speed (a) and impact energy (b)

Figure 5/b shows that a small car (1000 kg) with an impact speed of 30 km/h represents the same kinetic energy as a van (3500 kg) with 20 km/h impact speed. It may be read out from Figure 5/a that the equivalent impact speed of the bus producing the same kinetic energy – assuming a full frontal impact against a rigid wall – is about 6 km/h.

2.2. Protecting the bus and bus occupants.

The protection of the bus occupants has special importance when the bus collides a rigid wall, wall-like object or another heavy vehicle and the collision is full (not offset) For this case the working conditions of a safety bumper are shown on Figure 6. The safety bumper, as a complex system has three working ranges:

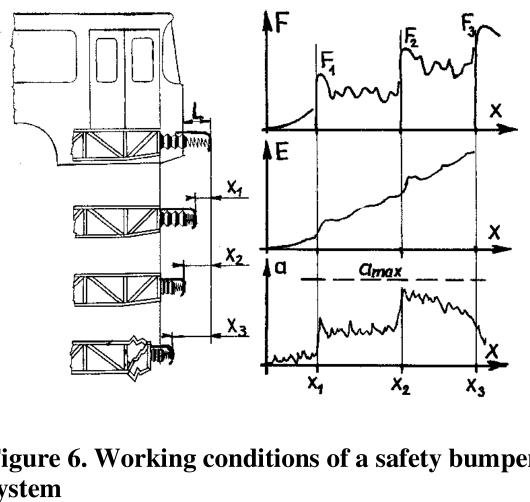

Figure 6. Working conditions of a safety bumper system

a) In the normal position (no impact, no load on the bumper) the bumper has a certain projection (L) from the front wall
b) The first working range (WR1) is a non-linear elastic deformation range having a maximum value $x_1 << L$ If the impact speed of the bus (v) is smaller than a limit value (v_1), no permanent deformation occurs, the bumper springs back, the impact energy is absorbed temporarily by the elastic deformation. This impact speed limit value could be rather low (e.g. $v_1 = 4$ km/h)
c) In the second working range (WR2) the bumper has a permanent, plastic deformation range ($x_1 < x \leq L$) If the impact speed is smaller than a limit value ($v_1 < v \leq v_2$) a permanent deformation will occur, but only in the bumper system, the front wall and other structural elements of the underframe structure remain intact. Practically it means that the bumper system has one or more structural elements, which absorb the impact energy while they are submitted to a certain plastic deformation. After the collision these elements are replaced by new ones and the whole bumper system is again in its normal position. The speed limit v_2 could be in the range of 15-18 km/h.
d) The third working range (WR3) is over the safety bumper capability, but it is strongly fitted to it. If the impact speed is higher than v_2 the safety bumper cannot absorb the impact energy, but in a certain speed range ($v_2 < v \leq v_3$) the impact should be controlled. For example the international regulation UN/ECE/Reg.80 describes the requirements for bus seats and seat anchorages in case of frontal impact with an impact speed of $v_3 = 30$ km/h. A certain deceleration pulse is assumed and described for seat tests for this standardized accident.

When designing and developing this kind of safety bumper system, a lot of technical parameters of the bus and the bumper shall be considered e.g. the mass, the impact speed, the allowed maximum deceleration or deceleration pulse, kinetic energy, etc. for the bus and the acceptable projection of the bumper, its energy absorbing capability, load bearing capacity, the main parameters of its working ranges, etc.

There are three basic criteria, on the basis of which these technical parameters shall be harmonized, fitted to each other in the three working ranges of the safety bumper system:

- Force criterion Figure 6. shows a typical force (F) – deformation (x) curve in the three working ranges (x_1, x_2, x_3) To assure the appropriate sequence of the working ranges during the frontal collision, the force in the whole lower working range shall be smaller than the force at the beginning of the next working range. (simply $F_1 < F_2 < F_3$) Otherwise the deformation in the next working range will start untimely, too early.

- Energy criterion. Every working range represents an impact speed limit which – considering the effective mass of the bus – determines a kinetic energy. This energy must be absorbed by the safety bumper, which means the bumper shall have this energy absorbing capability. The energy curve (E) on Figure 6 may be derived from the force curve (F) by integration.
- Deformation criterion. The working ranges of the bumper system belong to certain deformation ranges which are determined by two things: the energy absorbing capability and the maximum, allowable deceleration (deceleration pulse) It is interesting to mention that to day there is an administrative difficulty to develop and use safety bumper on buses. As it was shown above, to absorb energy, to limit the deceleration a certain amount of deformation (elastic and plastic together) is needed which means that the bumper requires a certain projection (L) from the front wall. To be effective this projection could be in the range of 250-350 mm. The total length of the bus – per definition – includes the bumpers too and every country, the national authorities determine length limitations for the large vehicles. Therefore to increase the projection of the bumper could mean to reduce the seat spacing (comfort of the passengers) or reduce the number of the seat rows (economy of the bus service) Therefore the bus operators and the manufacturers – without legislative force - are not enthusiastic for the safety bumper.

3. SAFETY BUMPER DEVELOPMENTS

3.2. Buses with experimental safety bumper

The development of a safety bumper system needs a lot of work: design considerations, laboratory tests and finally the validation of the whole effort by full-scale impact test of the bus. In the following some examples are shown about this development process. IKARUS Bus Manufacturing Co., working together with Research Institute of Automobile Industry produced and tested two buses with safety bumper systems [1]:

– Prototype of a 12 m long high decker long-distance tourist coach, type IK270 (see Figure 7.) The safety bumper concentrated to the partner protection: its surface was covered by a 40 mm thick square net plastic foam structure (see Figure 19.) The energy absorber was built from aluminium honeycomb (plate thickness 1,5 mm) filled up with plastic foam. Between the bumper structure and the underframe of the bus, two air springs were used, providing a 80 mm spring-way to decelerate the bus in total frontal collision. The air springs were non-linear elastic springs, so their energy absorption was temporally, they sprung back after the collision.

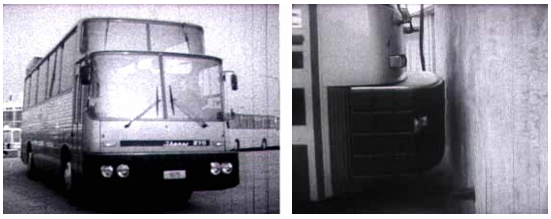

Figure 7. Long distance HD coach with safety bumper, before low speed impact test

– Serial version of a 11,4 m long IKARUS city bus – type IK 415 – with safety bumper, see Figure 8. The main goal of the bumper was to protect the bus occupants in total frontal collision.

The underrun protection was not a central issue in these two projects.

Figure 8. City bus with safety bumper, before impact test

3.2 Design considerations.

As an example, the design considerations and efforts will be shown with the city bus bumper development. The task was to develop a new safety bumper to an existing bus type (IK 415) which was already in serial production. The possible projection of the bumper from the front wall (L) was limited by the national total length limitation (12 m) and also the position, location was determined by the front wall structure and shape. The engineering lay out of the safety bumper may be seen on Figure 9. The goals were:

I. In WR1 no plastic deformation is allowed up to the impact speed v_1 = 4 km/h

II. In WR2 the energy is absorbed by plastic deformation of a removable part, the max. impact speed is v_2 = 8 km/h. No damage is allowed in the front wall structure.

III. In WR3 the plastic deformation of the underframe structure should be localized also to a changeable part, but the front wall damage is acceptable. The maximum impact speed v_3 = 30 km/h and the deceleration of the bus CG's shall be in the pulse given in ECE. Reg.80.

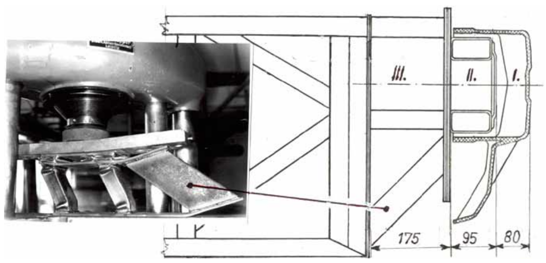

Figure 9. General layout of the safety bumper

To meat the three criteria described in para. 2.2. laboratory tests were needed to know something more about the structural elements, structures used in the safety bumper system.

3.3. Laboratory tests.

Many, different kind of laboratory tests have been carried out to get information about the behaviour of different structural elements. Figure 10. shows the force-deformation characteristics of non linear elastic rubber elements. The hysteresis in these rubber elements is rather small (15%) so their real energy absorbing capability is not significant. To the combined rubber structure shown on Figure 10. (three double elements) having deformation of 60 mm belongs a total energy of ≈ 15 kJ, while the really absorbed energy is around 2 kJ, the other 13 kJ belongs to the elastic spring return.

The underframe structures of the two buses equipped with safety bumper were built up from rectangular steel tubes. Therefore it is important to know the crash behaviour of these tubes. On the other hand these tubes may be used as components of energy absorber structures, too, therefore more hundreds of laboratory tests were carried out. Some examples are shown on Figure 11. where the crash characteristics, the buckling behaviours of rectangular steel tube (cross section 40x40x2 mm) and tube combinations are given. Some interesting conclusion of these curves:

- The buckling force (the first, highest peak of the curve) is almost linearly related to the area of cross sections of the tube combinations.

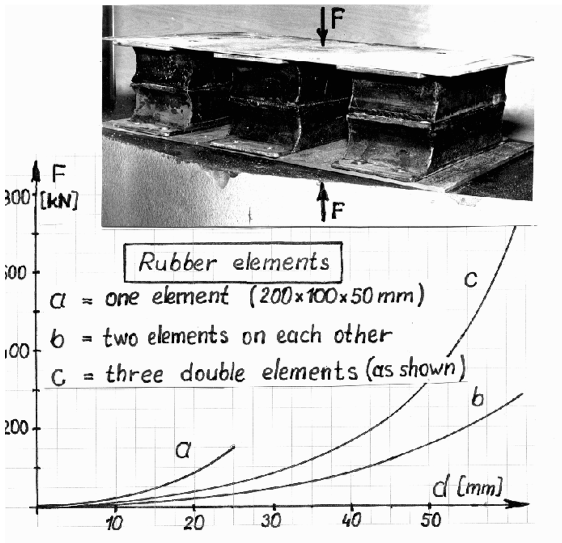

Figure 10. Force-deformation curves of rubber elements

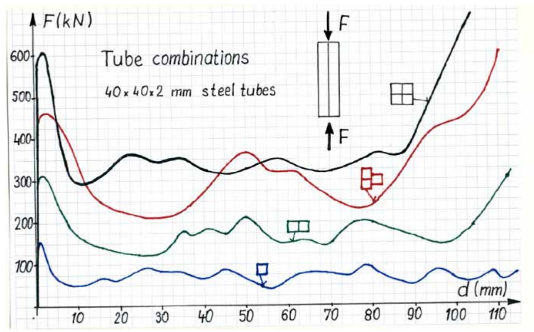

Figure 11. Force-deformation curves of rubber elements

- The hardening part of the curves (the last part, where the force is continuously increasing) does not show any close relation to the area of cross sections.
- The stable energy absorbing part of the curves (middle part between the first buckling and the hardening) there is a significant correlation between the area of the cross section and the absorbed energy.
- The buckling deformation process, the folding of the tubes, tube combinations are similar. Figure 12. shows the folding of a single tube, having a cross section of 40x40x2 mm and also the buckling of four tubes combination with the same cross section. Figure 13. gives two stages of the folding process of a two tubes combination.

Figure 12. Folding of a single tube and four tubes combination

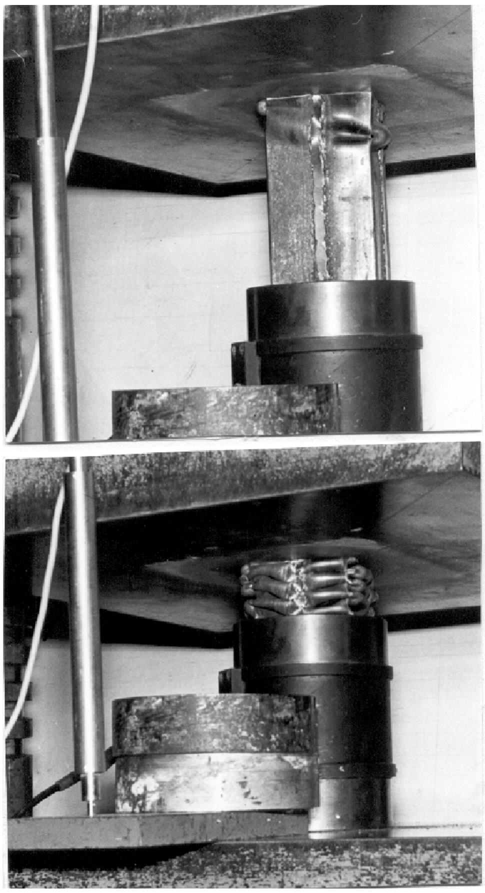

Figure 13. Folding process of a double tube combination

It is interesting to mention that the different arrangement of a tube combination (in which the area of the cross section is the same) may result significantly different buckling and energy absorbing behaviour. Figure 14. compares three different arrangements of the two tubes combination, in which the position of the tubes to each other are different. The significant differences are obvious.

There are two interesting phenomena which should be mentioned in relation to the folding buckling of tubular structures and should be considered when designing crashworthiness of bus frames, when calculating safety bumpers, energy absorbing elements built up from tubular structural elements. To meet the three basic criteria in the working ranges of the safety bumper discussed in para 2.2. these are essential phenomena:

- The compressed tubes may lose their stability on two ways, depending on the length of the tube [2] The "short" tubes have folding type buckling while on the "long" tubes rotational plastic hinges are formed. Between the "short" and the "long" ounces there is a transitional range in which both kind of loss of stability may occur accidentally. The "short" and "long" terms depend on the cross sectional parameters of the tubes (thickness area, ratio of the sides, etc.) Figure 15. gives an example measured on 40x40x2 mm tubes. The two curves represents two different force applications: one was through free end of tube (free deformation capability of the end of the tube) and the other through fixed end. (Welded plate on the end, no deformation capability)

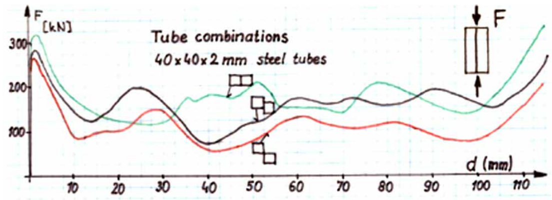

Figure 14. Force-deformation curves of different double tube arrangement

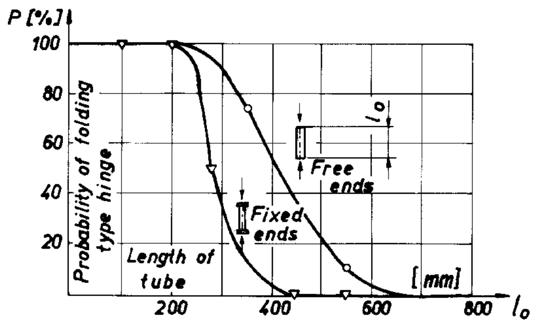

Figure 15. Probability of folding type buckling as function of tube length

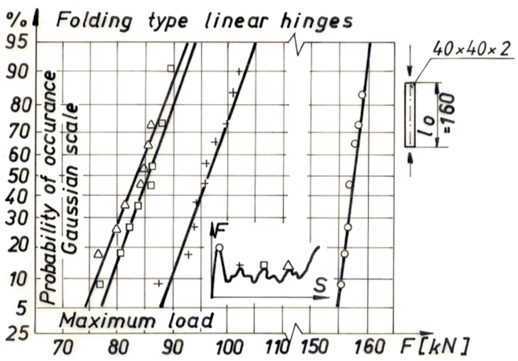

Figure 16. Distribution functions of force maximums.

- The folding process is random one, influenced by a lot of small accidental effects. All parameters of a force-deformation curve may be represented by a probability distribution function. As an example, Figure 16. shows the distribution functions of the local force peaks on the force-deformation curve. Ten 40x40x2 mm rectangular tubes were compressed with a length of 160 mm having free ends and their force deformation curves were analysed. The distribution of the first, second, third and fourth force peak are shown in Gaussian normal coordinate system. The mean value and the scatter of the distributions may be determined from these figures.

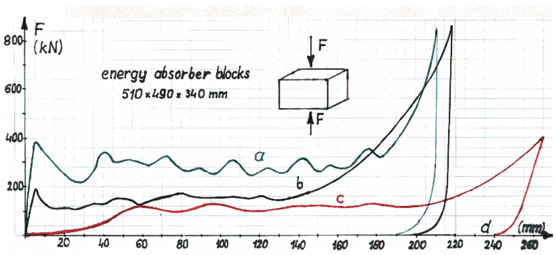

Figure 17. Force-deformation curves of energy absorber blocks

Another test series was carried out with special energy absorbers. Figure 17. shows the force-deformation curves of three energy absorber blocks (EAB) having the same dimensions (510x490x350 mm) but different construction:

a) Steel plate box (thickness: 0,5 mm) with a rectangular tube (40x40x2 mm) in every corner, welded to the plates with intermittent welds. The box was filled up with polyurethane foam (density: 80 kg/m^3) See Figure 18.
b) Spot welded steel plate honeycomb structure (plate thickness 0,5 mm 14 sub-boxes in the EAB) filled up with polyurethane foam (density: 50 kg/m^3)
c) Aluminium honeycomb structure (thickness: 1,5 mm) filled up with polyurethane foam (density: 50 kg/m^3). The surface of this EAB was covered by square net plastic foam, see Figure 19. This structure was used as the safety bumper of the prototype IK 270 long distance coach.

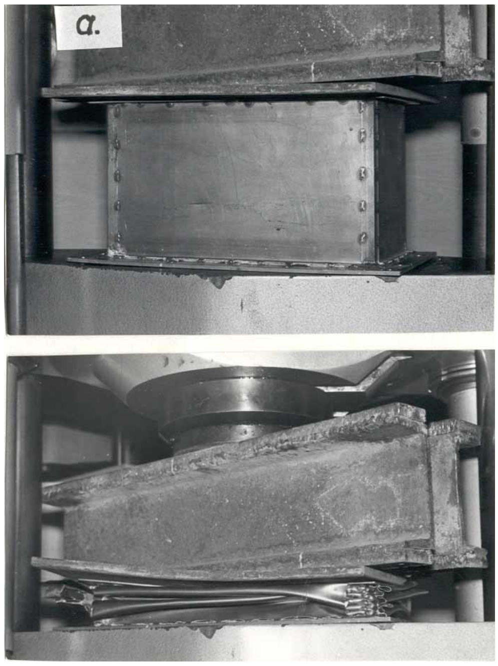

Figure 18. Test of a possible energy-absorbing block

Figure 19. Test of energy absorbing block of IK270 experimental coach

It is interesting to mention: in the case “a” the expected maximum force (loss of stability) was over 600 kN (Figure 12. shows that this value for one tube is more than 150 kN) Very likely the load distribution among the tubes was not equivalent, first two tubes on one side started the folding and after that the reminding two ones on the other side.

The test series was extended to compare the static and dynamic behaviour of energy absorbers. The dynamic tests were pendulum impact tests. Figure 20. compares the static and dynamic force-deformation curves of 40x40x2 mm steel rectangular tubes. Figure 21. shows similar diagrams for EAB type "b" (see above)

One of the main conclusions of these kinds of comparative tests is the hardening effect in the dynamic tests:

– The energy absorption, belonging to the same deformation (d) is higher in dynamic circumstances. In the case of steel tubes the ratio E_{dyn}/E_{st} is 1,2-1,3 but the honeycomb energy absorber showed a much higher ratio: 1,5-2,0
– On other hand this means that the same energy absorption belongs to smaller deformation in the dynamic tests.
– It was also observed that the dynamic tests produced cracks and fractures earlier, at smaller deformations than the static tests.

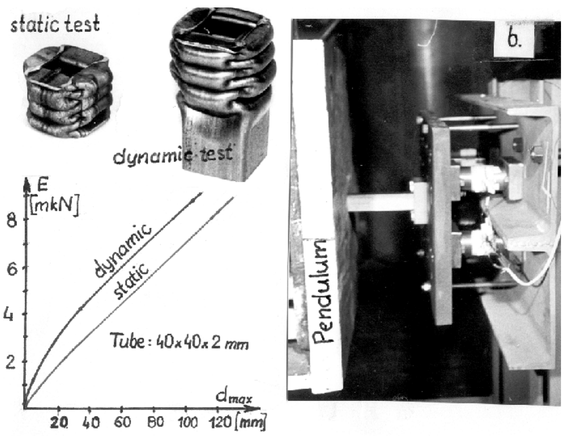

Figure 20. Static and dynamic behaviour of tubes

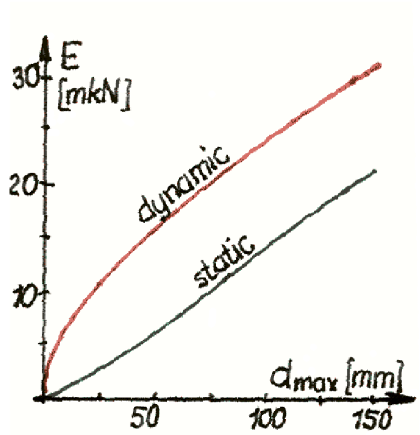

Figure 21. Static and dynamic behaviour of EAB

It is a key issue to have good, reliable correlation between the static and dynamic behaviour of the structural elements because in this case it is enough to make the much simpler and cheaper static tests in the early phase of the development.

3.4 Full scale impact tests

The validation of the development process (design, calculations, laboratory tests) could be a full-scale dynamic test, which may be carried out by a test bus impacting a rigid wall or the simulation of this impact e.g. by an appropriate pendulum test. Full-scale impact tests have been made with the type IKARUS 415 having the safety bumper, discussed in chapter 3.2. Figure 8. shows the test arrangement. According to the WR-s of the safety bumper four impact tests have been carried out, in WR1 and WR2 the real impact speeds were a little bit smaller than the planned ones: 3 km/h and 3,6 km/h (two tests, instead of 4 km/h) and 7 km/h (instead of 8 km/h) Figure 22. shows some of the measured parameters in these impact tests:

a) The total impact forces (two force transducers were used) as the function of time
b) The maximum values of impact forces and deceleration of the bus CG's as the function of the impact speed.

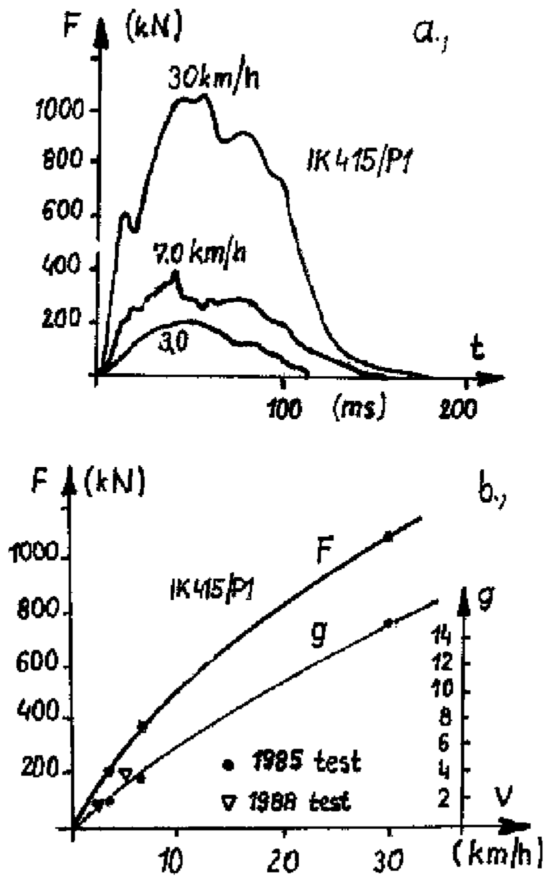

Figure 22. Measured values in frontal impact test.

The general evaluation of the test results, evaluation of the experimental safety bumper:

- In WR1 the safety bumper behaved well, there was no permanent, residual deformation after the two impact tests.
- In WR2 we had to realise a malfunction of the safety bumper system. Part II. (see Figure 9.) was too rigid compared to Part III. The requirement $F_1 < F_2$ has not been met, or in other words, Part III. started to work earlier than Part II., more exactly only Part III. worked and absorbed the energy, Part II. remained intact. The deformation of Part III. was a little bit bigger than it was planned for Part II., therefore the front wall (its panelling) was slightly damaged

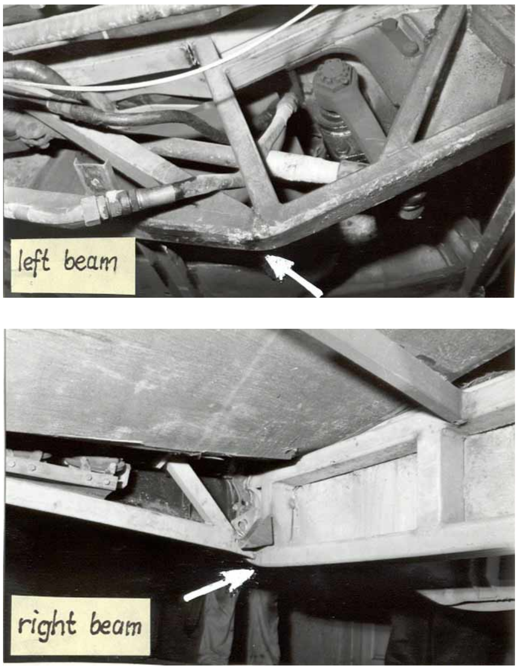

Figure 23. Deformation of the longitudinal beams of the underframe

- Replacing the deformed Part III. by a new, reinforced one, the last test checked the behaviour of the safety bumper system in WR3. To correct one mistake – as usually – creates a new mistake. Reinforcing Part III., now the underframe structure proved to be too weak, now the requirement $F_2 < F_3$ has not been met, so the longitudinal beams of the underframe structure endured undesirable deformations as it is shown on Figure 23. The two longitudinal beam had different construction because of the driver compartment (left side) and the staircase at the service door (right side) It is interesting to point out that the expected strength of these underframe beams were based on test result of tubes and tube combinations. But the phenomena discussed above (two possible ways of losing stability as the function of tube length, probability approach and the effect of the load distribution) were not recognized and considered yet.
- Structural parts, elements, components which are equivalent in respect to the normal service loads (linear stress-strain relationship, only elastic deformations) can behave completely different way when they are subjected to crash loads. Small local constructional differences can create essential differences in the initiation and working of plastic hinges, between their characteristics. The locality has much higher importance when designing structures for crash loads.

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[2] Matolcsy M. Crashworthiness of bus structures and rollover protection. Crashworthiness of Transportation Systems: Structural impact and Occupant protection. 1997 Kluwer Academic Publisher. Eds J.A.C. Ambrosio et al. p. 321-360.