ONE OF THE POSSIBLE METHODS OF SHAPING THE CHARACTERISTICS OF ENERGY DISSIPATION IN THE MOTOR VEHICLE STRUCTURE

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Summary

The importance of safety among all the factors that are taken into account by customers when planning to buy a car has been highlighted. The main factors concerning the shaping of passive safety of a motor vehicle have been described and guidelines on the assessment methods to be employed at the research work in this field have been given. The energy dissipation vs. vehicle body deformation curves that may be observed at frontal collisions have been discussed. The curve shapes that may represent favourable or adverse impact of the energy dissipation characteristics on vehicle occupants' chances to survive inside the vehicle body have been indicated. To obtain favourable energy dissipation characteristics, the authors have proposed their own engineering solution in the design of longitudinal vehicle bodywork beams. The energy dissipation process was improved by reinforcing the longitudinal beam models with special elements welded to beam walls. An assumption was simultaneously made that the shape of the energy dissipation curve might be controlled by the type and arrangement of individual welds. The beam models were actually made and used as specimens tested on a strength-testing machine at a certified laboratory at the BOSMAL Automotive Research and Development Institute in Bielsko-Biała. Energy dissipation curves determined for test specimens without and with the reinforcements have been presented herein. The test results obtained have been compared with each other and assessed in both qualitative and quantitative terms. The publication has been based on a student's graduation work done by Michał Szuberla under the supervision of Kazimierz M. Romaniszyn.

Keywords: passive safety, energy dissipation.

1. Introduction

The general issues related to safety are now counted among the most important vehicle assessment criteria, from the point of view of vehicle designers, builders, as well as buyers. Dynamic development of the automotive market results in intensification of road traffic and, in consequence, in a growing number of accidents.

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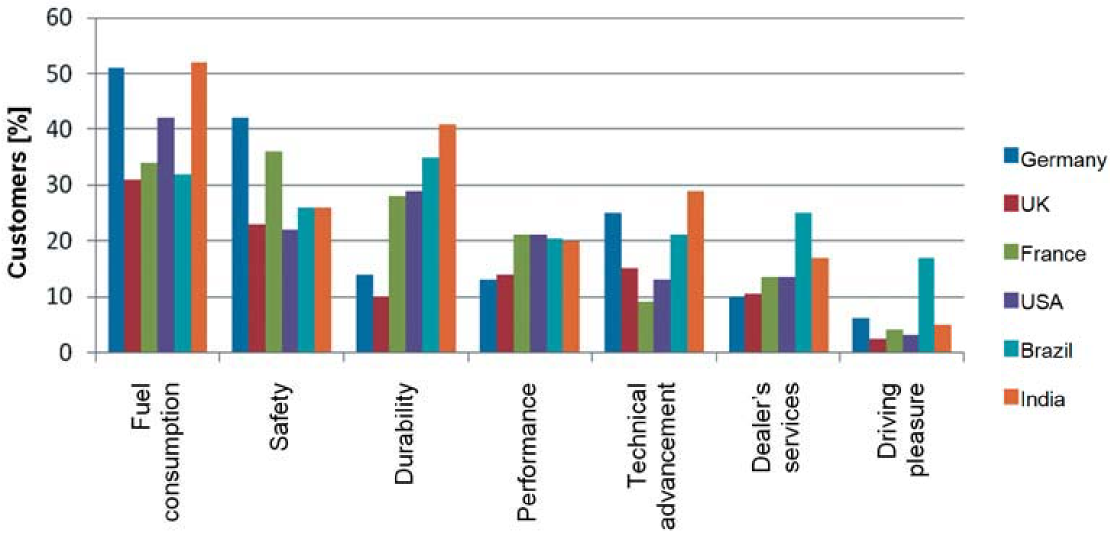

Fig. 1. Preferences of vehicle buyers [1]

Therefore, more and more buyers of new vehicles pay attention not only to economy or trouble-free operation but also to the safety level offered by a specific vehicle model [1, 3]. Fig. 1 shows a comparison of the preferences chiefly taken into account by the buyers of new vehicles in a few selected countries.

It may be observed that in the rich countries, such as Germany, France, the UK, or the USA, safety is one of the most preferable factors taken into account by the buyers of new cars.

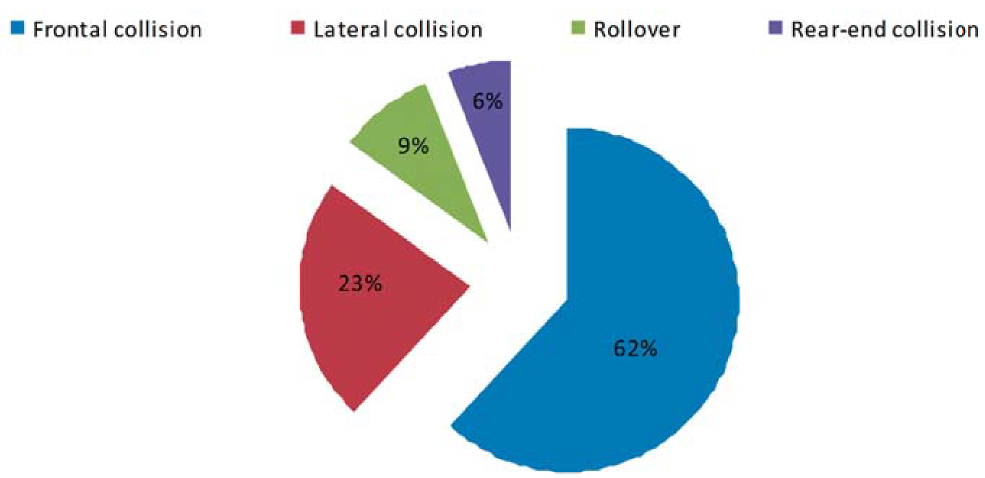

Fig. 2. Statistics of road accidents, according to Daimler [1]

On the other hand, low fuel consumption and durability are considered most desirable by the buyers in less affluent communities.

An analysis of the statistical data of road accidents shows that frontal collisions take the highest share (over 60%) in the total number of the accidents (Fig. 2). This causes vehicle designers to pay much attention to appropriate shaping of the vehicle front: this part of the vehicle structure should ensure controlled absorption of the energy of impact. The accomplishment of this task depends on the engine location within the vehicle body. If the engine is situated at the front then the front axle load is increased and the vehicle shows a tendency to "dive" during a collision, i.e. to slip under the other vehicle participating in the collision. In the case of a rear-mounted engine, the vehicle front is lightened and this causes the characteristics of the vehicle impact to be changed. The engine coupled with the gearbox constitutes a unit of high mass; in consequence, significant forces of inertia are generated during a collision and these forces participate in the crumpling of the passenger compartment if the engine is situated at the back.

A much more difficult challenge is to ensure adequate energy absorption at lateral collisions, which make more than 20% of road accidents, according to statistical data. Predominantly, they are collisions with other vehicles or roadside objects, e.g. trees, poles, etc. In the event of a collision with another vehicle, the other vehicle absorbs a part of the impact energy, but when a collision with a tree or pole is involved, the whole impetus of the impact is taken over by the side part of the vehicle body. Another unfavourable factor is small distance of the driver from the external side contour of the vehicle, which entails the necessity of applying stiffer reinforcements to transmit the energy of impact to other components of the vehicle bodywork. In this paper, the improvement of safety at frontal collisions, which most frequently occur, has been exclusively addressed.

2. The main factors that determine the passive safety

In Europe, the regulations to be observed include decisions of the United Nations Economic Commission for Europe (UN ECE), within which the Working Party on Road Traffic and an Expert Group subordinate to the said Working Party started their work in the field of the construction of vehicles in 1953. The basic document is "Agreement Concerning the Adoption of Uniform Conditions of Approval and Reciprocal Recognition of Approval for Motor Vehicle Equipment and Parts" (Geneva, 1958)[3] [2].

Apart from this, the European Union has its own legal standards formulated in documents referred to as Directives of the European Economic Community (EEC) or the Council of the European Union (EC). Some of them coincide with the ECE requirements.

Examples of the EU Directives and the corresponding UN ECE Regulations concerning the safety of passenger cars have been given in the table below.

[1] This is the title of this document in its version of 1958; the current document title is "Agreement concerning the adoption of uniform technical prescriptions for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions" (http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/505ep29.pdf). Translator's note.

Table 1. [4]

Subject of the approval	EU Directive	UN ECE Regulation
Protection of the driver from an impact against the steering mechanism in the event of a frontal collision	74/297/EEC	R 12
Braking of passenger cars	71/320/EEC	R 13-H
Safety-belts and restraint systems	77/541/EEC	R 16
Safety-belt anchorages	76/115/EEC	R 14
Strength of seats, their anchorages and head restraints	74/408/EEC	R 17
External projections of motor vehicles	74/483/EEC	R 26
Protection of the occupants in the event of a frontal collision	96/79/EC	R 94
Protection of the occupants in the event of a lateral collision	96/27/EC	R 95

The "ensuring of passive safety" has a meaning identical to that of "reduction of the severity of possible accident effects." The main objectives are to protect driver and passengers' life and to minimise the risk of severe injuries occurring in consequence of an accident.

These objectives may be pursued by applying the following solutions:

- Appropriate vehicle body design (with the front and rear part of the body being prepared to absorb as much as possible of the impact energy and the central body part performing the function of a so-called "safety cell", i.e. constituting a sufficiently rigid and robust structure), as well as reinforcements of side doors, pillars, rockers, and roof;
- Safe side door locks (preventing the doors from accidental opening during a collision and simultaneously maintaining the possibility of the doors being opened after the accident);
- Safe windows (which would not cause vehicle occupants to be cut by pieces of glass when broken and would provide a possibility of the windows being safely pushed out after the accident);
- Flexible steering column, so designed that any displacement of the column into the vehicle interior during an accident should be prevented;
- Safety belts with belt tensioners electronically controlled and with belt tension limiters;
- Airbags (driver and passenger front airbags and side airbags, protecting vehicle occupants' heads and knees);
- Front seats provided with head restraints (active head restraints) with adjustable headrest height;
- Safe fuel tank (provided with a device to cut off the fuel supply in the event of an accident and a device to block any fuel outflow in case of vehicle rollover);
- Electrical system with a possibility of disconnecting the power source (a battery) after a collision;
- Vehicle interior made of soft inflammable materials properly shaped and meeting the applicable safety standards.

The present-day passenger cars have bodies with their stiffness being not uniform over the whole body length. This is due to the necessity that the vehicle body should comprise

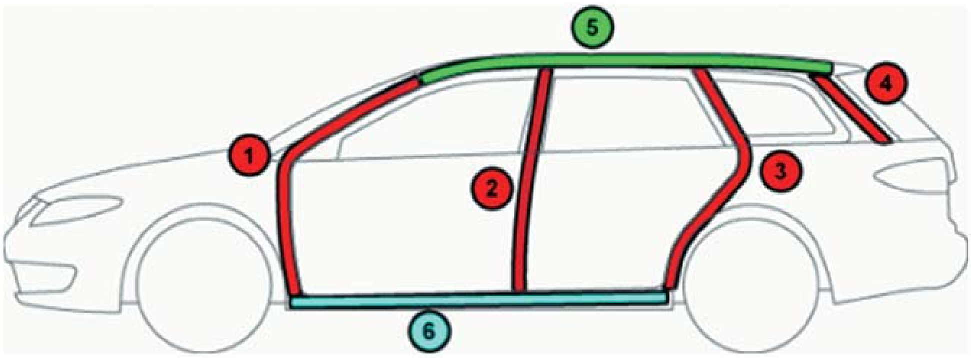

Fig. 3. Schematic diagram of the safety cell for the driver and passengers [6]:
1 – pillar A; 2 – pillar B; 3 – pillar C; 4 – pillar D; 5 – reinforced roof structure;
6 – reinforced floor and rockers structure

zones capable to absorb a significant part of the energy released during a collision. In the event of a frontal collision, the energy is taken over, in succession, by front bumper, front body panel, longitudinal beams, and internal mudguards. Three basic zones may be distinguished within the vehicle bodywork built in compliance with the stiffness gradation principle: the front and rear energy-absorbing parts and the rigid and robust passenger compartment, constituting a so-called "safety cell" for the vehicle driver and passengers. An example of the arrangement of structural components of the passenger compartment can be seen in Fig. 3. One of the precursors of safety cell calculations was Janusz Pawłowski [5], who developed a calculation method named "PPK" ("Simple structural surface").

The diversification of the above zones in the vehicle bodywork is possible thanks to both the use of different materials for the making of individual body parts and the special shaping of these parts. In the event of a frontal collision, the energy is taken over by front bumper, front body panel, chassis cross-member, longitudinal beams, and internal mudguards (Fig. 4). The role of these elements is also to transmit the forces to structural nodes, from which the forces disperse around the cage that protects the passenger compartment (but without causing the cage to be deformed). The Kielce University of Technology organises cyclic conferences dedicated to the safety of road traffic. Numerous publications by Prof. Jerzy Wicher, Prof. Zbigniew Lozia, and Prof. Leon Prochowski dealing with passive safety issues, including energy dissipation at vehicle bodywork deformations, may be found in Zeszyty Naukowe (Scientific Bulletin) issued by the University.

The longitudinal beams play a particularly important role because they are the structural members that are chiefly accountable for the absorption of the impact energy [11]. They can fulfil this function thanks to their special shapes, cross-sections, dimensions, and structural materials. Moreover, they have special deformation areas "pre-programmed" at the vehicle design stage, provided for the possible energy dissipation process to run in a controlled way in case of need.

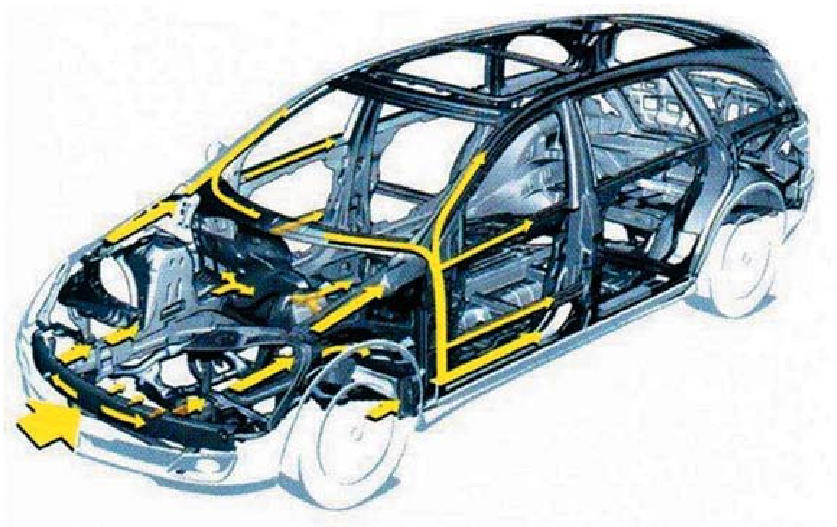

Fig. 4. Distribution of forces to specific parts of the vehicle bodywork during a frontal collision [4]

3. Energy dissipation by bodywork elements

The bodywork of a modern passenger car is so designed that in the event of a collision, it should undergo a process of controlled deformation in the zones specially provided for this purpose. The essence of such a solution is that as much as possible of the impact energy can thus be absorbed before the energy reaches the passenger compartment. Thanks to this, the accelerations acting on vehicle occupants would be reduced to the values that could be tolerated by occupants' bodies. Fig. 5 presents a graph that illustrates the difference in the distributions of vehicle body accelerations at a frontal impact of the car with a speed of about 50 km/h for the car having a rigid or flexible front part of the bodywork.

It can be clearly seen in the graph that the impact load transmitted to the passenger compartment of a car with its front part being rigid is about twice as high as that occurring if the vehicle front structure is flexible.

The purpose of the proposed modification in the design of the beams present in the vehicle engine compartment is to achieve the aforementioned reduction in the level of accelerations acting on vehicle occupants during a frontal collision. An analysis of the graph in Fig. 5 shows that the most flexible element should be the longitudinal beam in its part situated just behind the front bumper and the rigidity of the beam should gradually increase in the rearward direction to prevent deformation of the passenger compartment. Plastic components insignificantly affect the characteristics of the crumpling process [9]; however, the application of new structures that can considerably raise the bodywork stiffness can be observed. The use of parts made of carbon fibre and composites is chiefly meant here.

Conformity with these requirements was achieved by differentiation of the cross-sectional area of the proposed longitudinal beam models along the beams' centreline. The beam

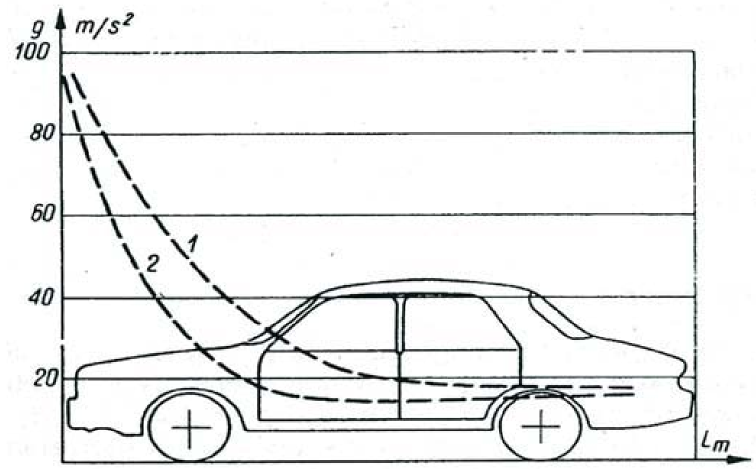

Fig. 5. Distribution of bodywork accelerations at a frontal collision with a speed of 50 km/h [4]:
1 – Rigid front part of the bodywork; 2 – Flexible front part of the bodywork

cross-sectional area is the smallest at the front beam end (just behind the front bumper) and increases with approaching the passenger compartment, which results in gradual growth in local rigidity of the beam (the proposed longitudinal beam models were shaped as truncated pyramids). For the occupants present in the passenger compartment, the maximum accelerations resulting from the process of energy dissipation as a function of vehicle body deformation are extremely important because they have an impact on the occupants' survival. The energy dissipation vs. vehicle body deformation curves have been shown in Fig. 6.

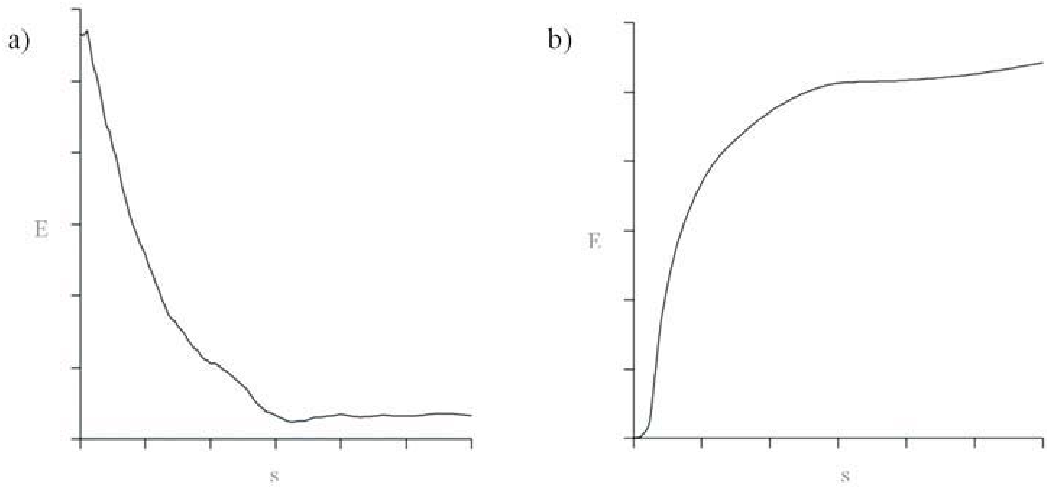

Fig. 6. Energy dissipation vs. vehicle body deformation curves [1].
Legend: a) – unfavourable shape of the curve; b) – desirable shape of the curve;
E – force; s – displacement

The unfavourable shape of the curve can be seen in Fig. 6a. In this case, the impact energy is intensively dissipated at the early stage of the crumpling process, which results in high acceleration values. In consequence, the energy dissipation chiefly takes place at this process stage. Conversely, the curve plotted in Fig. 6b shows that the energy (represented by force E) monotonically increases with increasing deformation (s). Thanks to this, the impact energy is dissipated in a controlled way before it reaches the passenger compartment and the value of the deceleration (negative acceleration) acting on vehicle occupants is thus minimised. The vehicle body designing guidelines where the passive safety is taken into account have been given in publication [8]. An analytical look at the development in the field of car body design and its characteristics has been presented in publication [10], where the author points out the searching for a compromise between various (and contradictory to each other in many cases) requirements set for passenger car bodies.

4. Testing of the modified longitudinal bodywork beams and their characteristics

The study was undertaken to work out models of longitudinal vehicle bodywork beams and to determine the energy dissipation characteristics of these models. The beam models were shaped as truncated pyramids; one of them was made as a thin-walled structure and another one was a structure of the same dimensions with additional flat bars welded inside it along the sidewall centrelines. The placement of the reinforcing elements inside the beam model resulted from the fact that such elements were likely to be installed inside the profiles to be actually used for a specific car. The proposed models of the longitudinal beams, used as test specimens as well, have been presented in Fig. 8. The adopted shape of the models proposed was to represent the engine mounting beams (longitudinal bodywork beams) of a real car, the front part of which has been visualised in Fig. 7. The drawing presented here was taken as a basis for numerical analyses carried out within other students' graduation works done with taking into account the results described in this publication.

Within the tests, deformation curves were determined for test specimen No. 1 (with no reinforcement) and test specimen No. 2 (reinforced with flat bars) and the curves were compared with each other and with the desirable shape of the impact energy dissipation vs. vehicle body deformation curve presented in Fig. 6b.

The test parameters set on the strength-testing machine Instron 1197 were identical for both specimens and they were as follows:

- Load range 200 kN
- Crumpling rate 50 mm/min
- Crumpling range 100 mm

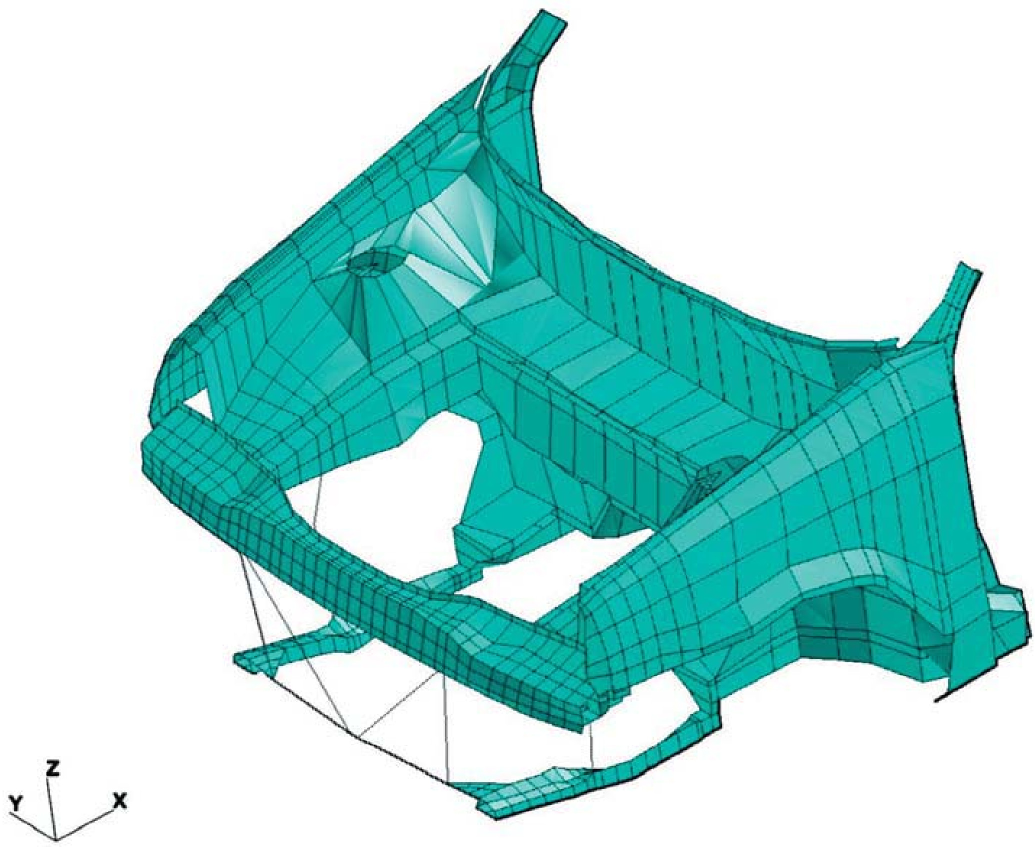

Fig. 7. Model of the front part of the bodywork of a passenger car

At first, specimen No. 1 (with no reinforcement) was tested and this was followed by a test carried out on specimen No. 2 (reinforced). The deformation curves based on the measurement data have been shown in Figs. 9 and 10.

Apart from the specimen deformation curves, energy dissipation curves were also determined from the measurement results.

The energy dissipated during the test was calculated as the area of the region under the loading force F vs. displacement L curve.

The deformation curves plotted for the two test specimens have been compared with each other in Fig. 11 and a comparison between the processes of energy dissipation by these specimens has been presented in Figs. 12 and 13.

Test specimen	Mass [g]	a [mm]	b [mm]	h [mm]	Sheet metal thickness [mm]	Reinforcement
Specimen No. 1 (without reinforcement)	1014	100	70	200	1.5	None
Specimen No. 2 (reinforced)	1681	100	70	200	1.5	Four flat bars made of steel sheet 1.5 mm thick, with dimensions 30×210 mm

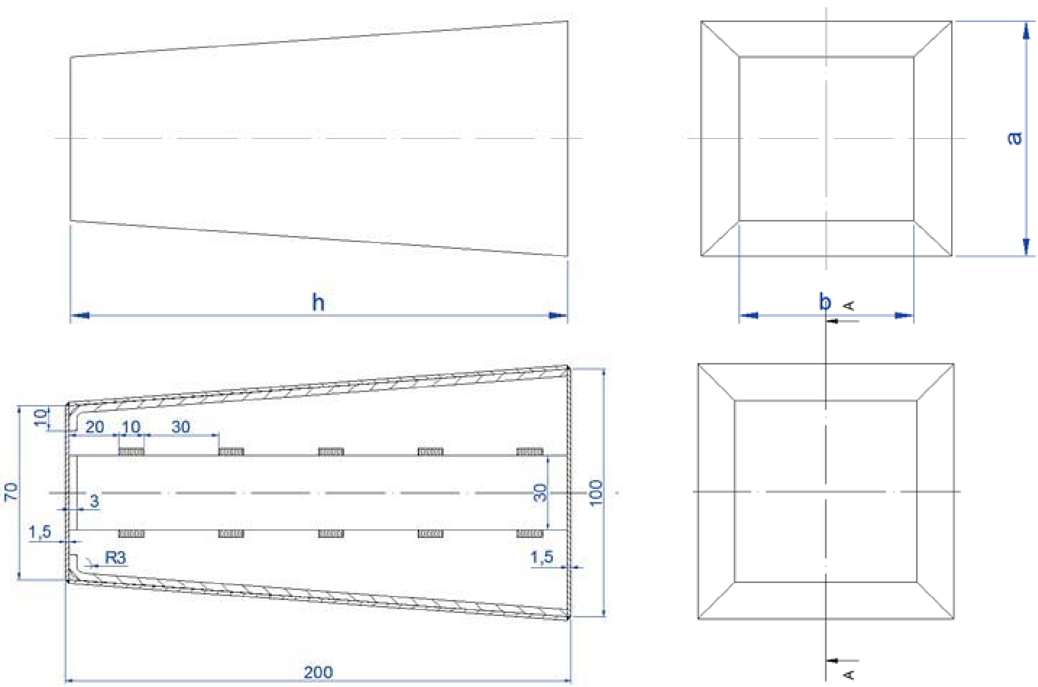

Fig. 8. Proposed steel models of the longitudinal beams, used as test specimens

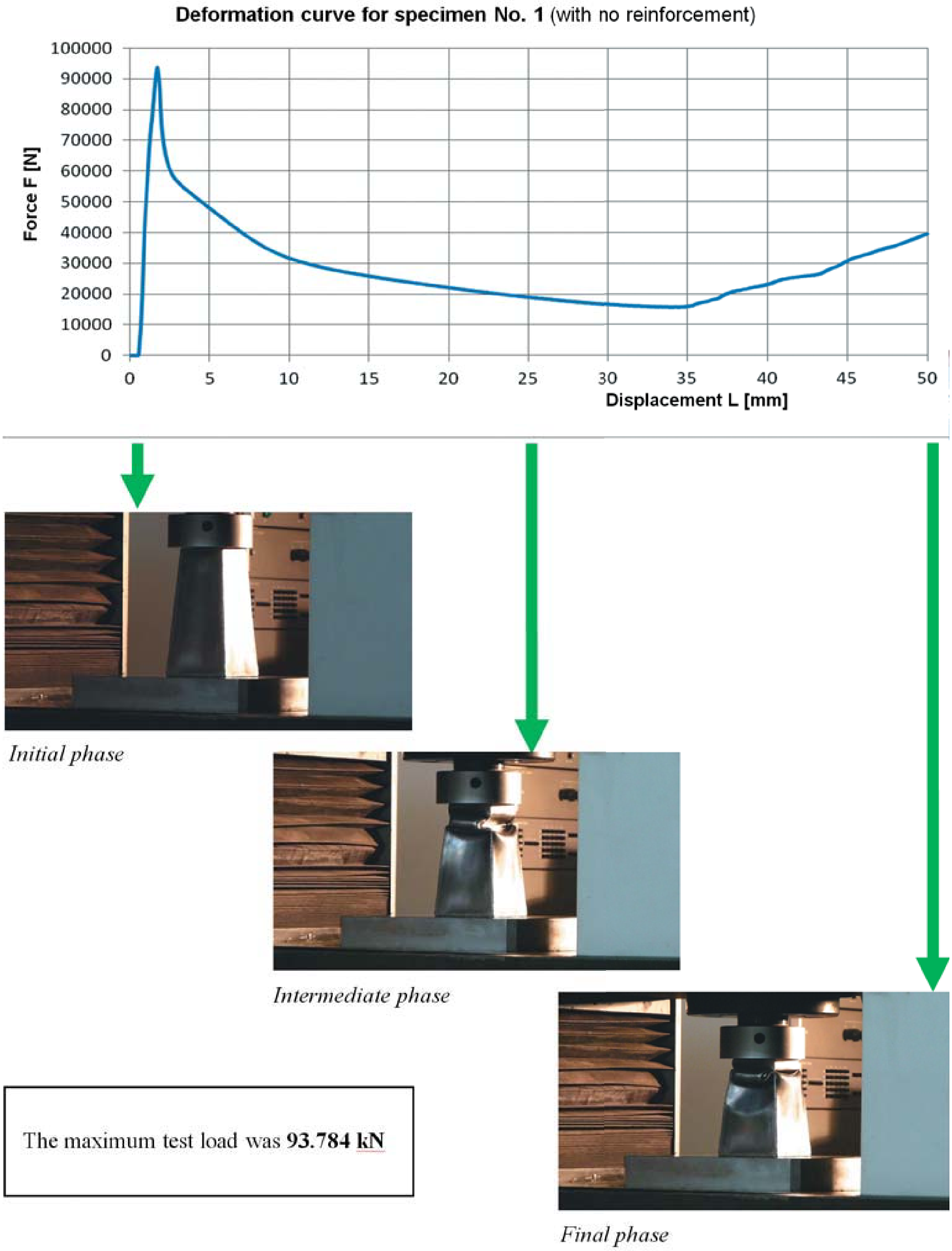

Fig. 9. The course of the crumpling test carried out on specimen No. 1

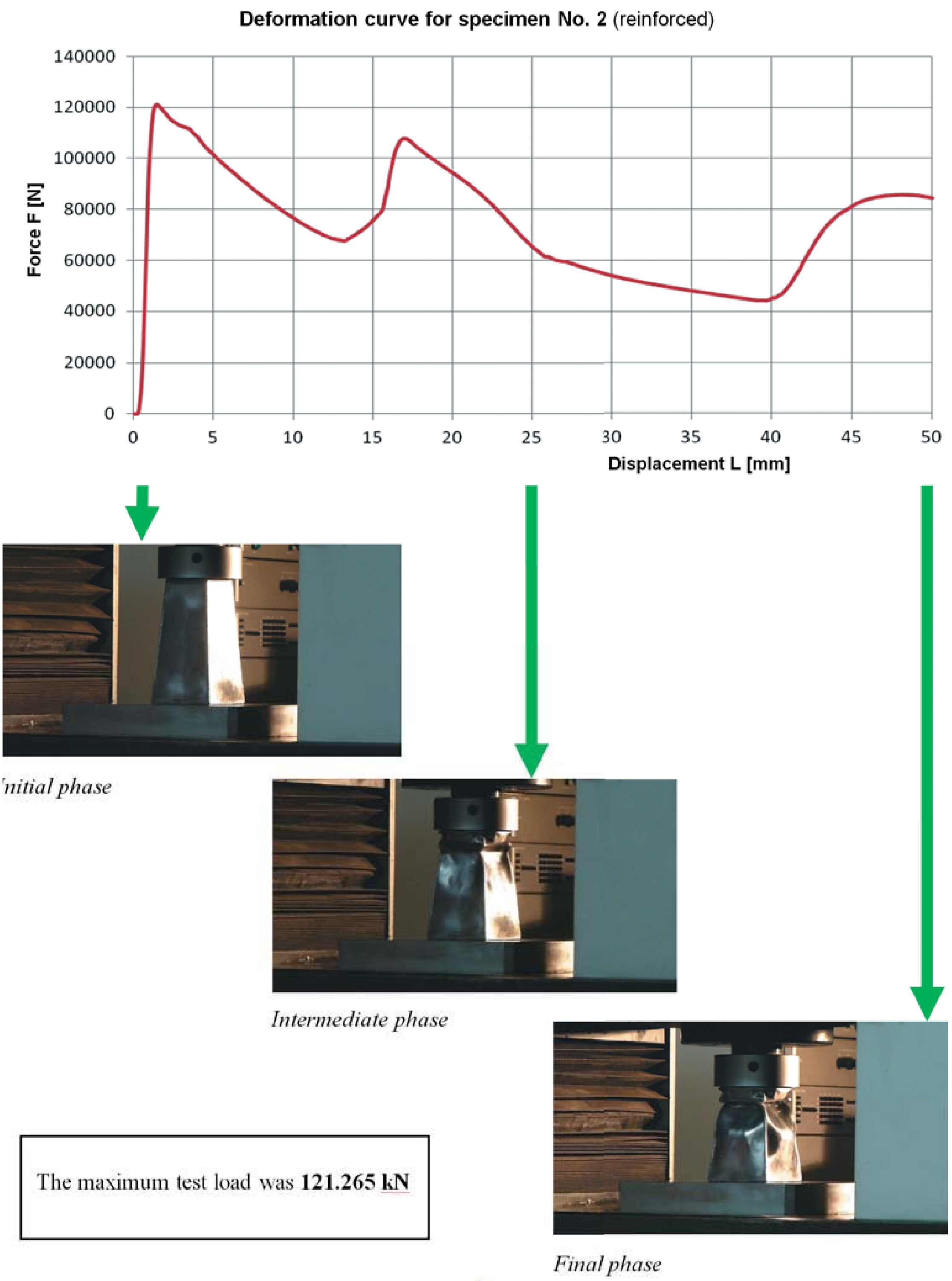

Fig. 10. The course of the crumpling test carried out on specimen No. 2

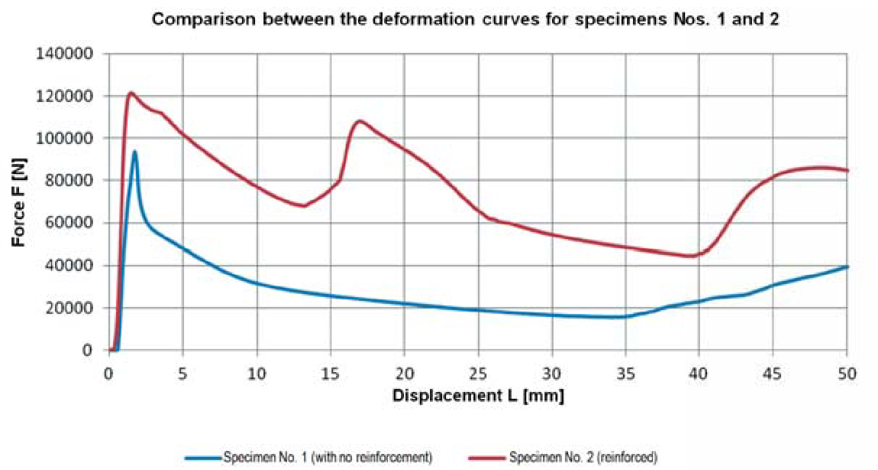

Fig. 11. Comparison between the deformation curves plotted for specimens Nos. 1 and 2

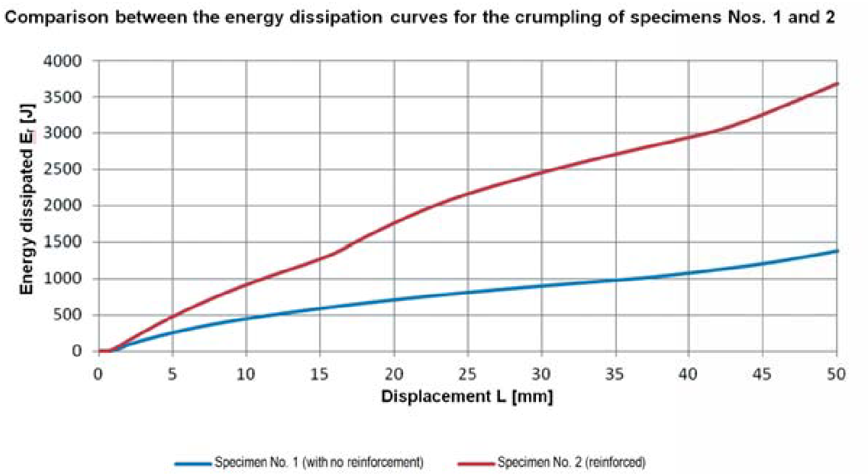

Fig. 12. Comparison between the energy dissipation curves plotted for specimens Nos. 1 and 2

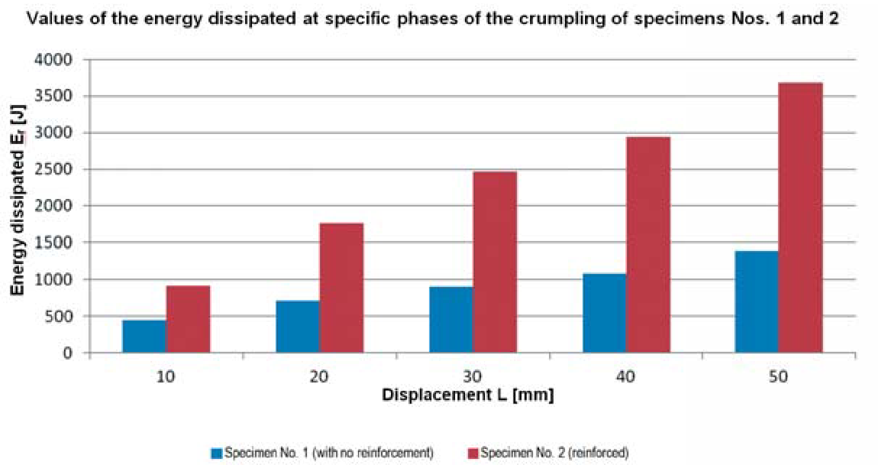

Fig. 13. Changes in the values of the energy dissipated vs. the specimen deformation

5. Analysis of the results obtained with conclusions

The tests carried out revealed a distinct difference between the deformation curves determined for specimens Nos. 1 (with no reinforcement) and 2 (reinforced). The maximum values of the compression force obtained for these two specimens were 93.7 kN and 121.2 kN, respectively. An analysis of this parameter of the deformation curves indicated also a difference in the stiffness of both specimens. The maximum value of the compression load for the reinforced specimen was obtained at an "earlier" stage, i.e. at a lower value of displacement L, which confirmed the stiffness of this specimen to be higher due to the flat bars having been welded inside the profile. Moreover, the deformation curve plotted for the reinforced specimen showed the compression force to rise when the deformation reached the level of the welded joints between the flat bars and the specimen walls (a local growth in the load to about 107 kN). For comparison, the load of specimen No. 1 having reached its top value continuously declined until the displacement grew to about 35 mm (with the force value having come then to about 18 kN).

When comparing the graph shown in Fig. 12 (representing the energy dissipation curves obtained from measurements) with the desirable shape of such curves (Fig. 6), we may notice an analogy regarding the monotonic energy growth with increasing displacement. This indicates the proposed concept of the longitudinal beam design to be correct. The phenomenon of energy dissipation during the crumpling process is more clearly visible for the reinforced specimen (No. 2) and this proves good effectiveness of the beam modification by the welding of flat bars inside the profile. Moreover, this fact shows that the course of the energy dissipation process may be controlled and "programmed" according to specific engineering requirements by selection of appropriate material for the energy-absorbing element, dimensions of this element, and reinforcements to be used.

A good point of the proposed modification to the longitudinal bodywork beam for a passenger car is the possibility of relatively easy "programming" of the characteristics of the crumpling energy dissipation process. In Fig. 10, rapid drop can be seen in the loading force immediately after the force comes to the first maximum, which reflects the reaching of the first welded joint. An improvement in this characteristic could be most probably achieved by placing the first welded joint closer to the upper base of the truncated pyramid constituting the beam profile and programming the spacing of individual welds. Another method of fastening the reinforcing element to the profile wall, e.g. spot welding with the welds being arranged to a specific pattern adopted, might be used as well.

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