
Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.

13th International Conference
on Applied Mechanics and
Mechanical Engineering.

COMPUTATIONAL AND EXPERIMENTAL STUDY OF ENERGY ABSORPTION METTER BY COMPOSITE STRUCTURES

NIEZGODA* T., BARNAT** W., MORKA** A.

ABSTRACT

The analysis considers the problem of transport safety improvement by application of additional impact energy dissipating elements. The results from experimental tests and numeric simulations of basic energy-absorbing element, in the form of sleeve made of steel and glass-epoxide composite are presented. These results were also used for the development of reliable numerical model of road barrier and for a simulation of barrier. The obtained results allowed for the practical usability assessment of the proposed solution.

KEY WORDS:

Transport, safety, protection barriers, and new technologies.

---

* Professor, Department of Mechanics and Applied Computer Science, Military University of Technology, Warsaw, Poland

** Resarch Associate, Department of Mechanics and Applied Computer Science, Military University of Technology, Warsaw, Poland

INTRODUCTION

The principal elements of presently used protective road barriers are: post, separator and guide rail (Figure 1). The first two elements mentioned are made of standard steel sections, such as double-tee bars and channel-irons. The sections of this type have good strength characteristics, but their energy-absorbing and vehicle impact energy dissipation capabilities are not satisfactory. They are generally available elements, that perform very well their role in many typical constructions, such as (bridges, railway over bridges, halls, etc.), requiring high durability, whereas in the case of road infrastructure, the energy-absorbing capability is of higher importance. Thus, there is a need for additional energy-absorbing structures in such elements, or to create completely new structures. It is noteworthy that the first solution does not require the replacement of existing barriers, but only to supplement them with some additional elements - quite important cost effectiveness aspect of such a project. These extra elements mounted to the road barriers have better energy-absorbing characteristics than rest of the barrier construction made of 3 mm thick steel sheet, and normalized profiles.

The part of the results (placed in the paper) was presented by the Authors in the article [1]. The bibliography data [2,3,4,10,11,12] deliver important indications, that the modification of existing structures with supplementary composite absorbing elements can decisively improve the effectiveness of impact's kinetic energy absorption.

The authors of the paper discuss the phenomena occurring during progressive collapse of composite structures, and the processes responsible for impact energy dissipation. In addition, the most popular computational techniques applied for these processes simulation, as well as own numeric tests are presented.

PHENOMENA OCCURING DURING DESTRUCTION OF COMPOSITE SAMPLES

The important element of acquiring a reliable numeric model and calculation results is to know and to define the process of destruction [5,6,7]. The most popular methods used for this aim are experimental ones. Nonetheless, currently available computers' calculation capacities allow for numeric support of the research.

The process of composite structure destruction in its microstructure consists of the following elements: destructions occurring in its singular cover, such as: fibres and warps cracking, fibres elastic buckling and fibres separation from the warp. It must be added that the process of loosening fibres from the warp is not only a question of mechanics, but also has its thermal and chemical aspects. For these reasons, an exact analysis of this process is difficult to conduct; particular layers' delamination. In macro scale, all above listed phenomena can occur in different proportions and scales, which is the reason of different global effects creation. As an example, one of typical experiments applied for composite materials energy-absorbing testing, is to subject the sample to axial compression (Figure 2). Experiments conducted by Farley, Hull [4,9] and other scientists indicate the presence of three basic mechanisms of samples' progressive destruction. They are: local buckling, transverse shearing and lamina bending. The destruction forms characteristic for the mechanisms above are schematically presented in Figure 2.

The calculation of energy absorbed during the process of composite structure failure as the sum of energy absorbed by the destruction process on the basic level (in micro scale) is very difficult to complete due to complex character of these phenomena; it is much easier to indicate the destruction energy on macroscope level.

COMPOSITE DESTRUCTION SIMULATION USING FEM

In this study uses for the destruction process of the material the Hashin model was applied. The model is based on the experience of Tsai-Wu model, due to isotropic tensile stresses. This model considers only fibres' stretching and compression, and warp's stretching and compression. The failure model is described by the following set of equations [8]:

$$\begin{cases} \text{Fibres' stretching:} & \left(\frac{\sigma_1}{X_T}\right)^2 + \left(\frac{\tau_2}{S_A}\right)^2 = 1 & (\sigma_1 > 0) \\ \text{Fibres' compression:} & |\sigma_1| = X_C & (\sigma_1 < 0) \\ \text{Warp's stretching:} & \left(\frac{\sigma_2}{Y_T}\right)^2 + \left(\frac{\tau_{12}}{S_A}\right)^2 = 1 & (\sigma_2 > 0) \\ \text{Warp's compression:} & \left(\frac{\sigma_2}{2S_T}\right)^2 + \left[\left(\frac{Y_C}{2S_T}\right)^2 - 1\right]\frac{\sigma_2}{Y_C} + \left(\frac{\tau_{12}}{S_A}\right)^2 = 1 & (\sigma_2 < 0) \end{cases} \qquad (1)$$

where: σ_1, σ_2 – principal stress components; X_C, X_T – maximum failure tensions in fibres (compression and stretching) in the direction 1; Y_C, Y_T – maximum failure tensions in fibres (compression and stretching) in the direction 2; S_T – maximal value of transverse shearing; S_A – shearing tensions in the layer's plane.

COMPARATIVE TESTS OF BASIC ENERGY-ABSORBING ELEMENT

The following chapter presents the comparison between the energy-absorption characteristics of two sleeves made of steel and of epoxide composite reinforced by glass fibre, having the same geometry. The sleeves shown in Figures 3 and 4 were used for the tests; their dimensions are presented in Table 1. The analysis has been performed using MSC.Dytran software based on finite elements method. The schema of partition network for finite elements of sleeve numeric model is presented in Figure 5. In the numerical model, the energy-absorbing models made of composite – glass mat and epoxide – had the following mechanical properties: $E_{1,2}$ = 6.8 GPa, $\nu_{1,2}$ = 0.27, $G_{1,2}$ = 3.8 GPa. For the modelling, the *SOLID* elements were used. In cases of both sleeves, i.e. glass one and epoxide one, numerical analysis was applied for the range of large displacements and deformations, taking into account the physical nonlinearity. Composite material model took into consideration Hashin failure criterion. The computations carried out were verified with experimental results from tests performed with INSTRON testing machine use.

Table 1: Numerical and experimental samples of composite and steel sleeves

	Composite sleeve	Steel sleeve
Mass [g]	20.72	98.72
Dimensions [mm]:		
- height	50	50
- internal diameter	40	40
- wall thickness	2	2

Steel Sleeve Tests Results

The experiment was carried out with an assumption of constant value of force velocity that was caused by movement of testing machine jaws with constant value of 10 mm/min. As result, it was obtained a diagram of compression force (reaction) in function of testing machine jaws displacement. This diagram is presented in Figure 6.

As a result of the experiment, it was found that the medium compression force is 70 kN. After taking into consideration of the path that testing machine jaws pass, the work of compression forces was estimated at 2,870 J. Taking into consideration the mass of tested element, it was found that the relative absorption energy for the steel sleeve is 29 kJ/kg. The above-mentioned case was submitted to the numerical analysis in which a numeric simulation of sleeve compression process was performed, similar to that carried out in the experiment. As a result of calculations carried out, a diagram of compression force in function of time was obtained. This diagram is presented in Figure 7.

On the basis of diagrams obtained, it can be observed that the diagram has a pitch character. Such a character of compression force course is caused by the development of two waves on the sleeve lateral edge. The steel sleeve deformation shape is presented in Figure 8.

Like in the case of diagram obtained from the experiment, the numerical diagram has also a pitch character, due to sleeve deformation character. Numerical results are coincident with the experimental records. Numerically obtained relative absorption energy is about 29 kJ/kg.

Composite Sleeve Tests' Results

Like in the case of steel sleeve, composite sleeve tests were investigated on the same testing machine, with the same jaws movement velocity 10 mm/min. As result of experiment, a diagram of compression force vs. displacement was obtained (see Figure 9).

At the initial scope, the diagram has linear character, but the value of the compression force obtained is maximum. In this scope, the imposed payload does not destroy the sleeve. Only when the maximum value is achieved it brings about the beginning of progressive destruction and the stabilisation of the destruction force. The level of maximum compression force can be reduced by using a so-called initiator (e.g. a phase on sleeve edge). The composite sleeve deformation character in form of its delamination is characteristic for progressive destruction (a so-called brush effect). The composite sleeve deformation shape is presented in Figure 10.

As the result of experiment, it was found that the average compression force is 23 kN. After taking into consideration the way that jaws of the testing machine pass, the work of compression force was estimated at 1,125 kJ. After taking into consideration the mass of tested element, it was found that the relative absorption energy of composite sleeve was 50 kJ/kg. It indicates that the relative absorption energy for the composite sleeve is almost two times bigger than the steel sleeve one. The above-mentioned case was also subjected to the numerical analysis. Like in the previous case, the simulation process took into consideration the experiment's conditions. As the result of calculations conducted, the compression force diagram vs. a time was obtained. This diagram is presented in Figure 11.

The diagram, obtained from numerical calculations, and presenting the compression force in function of displacement, indicates a similarity of a progressive destruction zone, but the difference takes a place in the first period of the loading increase due to lack of compression force increase to the maximum value. In this case, the structure is stiffer than its numerical model. The reason of this situation can be explained by the imperfection of material used. The composite sleeve deformation shape in numerical simulation process of composite sleeve loading is presented in Figure 12.

The results obtained during the numerical calculations show that for the medium value of compression force, the relative absorption energy is about 51 kJ/kg and match very well with the experimental one.

Conclusions to the Tests

The comparison of obtained results of the relative energy absorption for both tested sleeves (metal one and composite one), are presented in Table 2.

Table 2: Summary of obtained results

		Composite sleeve	Steel sleeve
Compression force [N]	experiment	23 000	70 000
	numerical calculations	26 000	75 000
Work of compression force on the 42 mm way [J]	experiment	1125	2870
	numerical calculations	1092	3150
Relative absorption energy [kJ/kg]	experiment	50	29
	numerical calculations	52.7	31.9

The results' compatibility for the relative energy absorption is a proof that numerical approach to the process of modelling of energy absorbed by the energy-absorbing elements of is sufficiently good (errors reach: 10% case of the steel sleeve, 5% composite sleeve). As results of numerical and experimental tests, it was found that the relative absorption energy of composite sleeves is two times bigger than for steel sleeves.

POST NUMERICAL MODELS' DESCRIPTION

In the successive part of the study, two cases of posts were subjected to the numerical analysis: steel one and steel with energy-absorbing element one. Two numerical models were developed for the analysis, with the following characteristics: the first model: road post made of steel double-tee bar, dimensions as following: height 0.7 m, width 0.1 m, depth 0.06 m, walls' thickness 3 mm and the second model, as presented in Figure 13, was similar to the first model. The only one difference was an additionally applied energy-absorbing element in a form of composite sleeve, with the following dimensions: height 0.05 m, external diameter 0.04 m, walls' thickness 0.005 m.

Three types of elements were applied for numerical models description: Steel stake was described with Shell type elements. Mechanical properties of steel elements were described by bilinear elastoplastic model (*DYMAT 24*). Maximum deformation of about 16% was pre-defined as failure criterion. The vehicle model was described as a non-deformable board with material properties described by *MATRIG* [7] card. It is defined by the mass (density) and thickness, which is important during contact mapping. In the model development, the energy-absorbing element was described with *SOLID* type elements. Energy-absorbing elements, just like those in comparison tests were associated with the following selected mechanical characteristics for the composite made of glass mat and epoxide (received from the experiment): $E_{1,2}$ = 6.8 GPa, $\nu_{1,2}$ = 0.27, $G_{1,2}$ =3.8 GPa. The numerical model contained 30744 nodes and of 22680 *SOLID* type elements. In the process of numerical simulation, the model were loaded with an impact force directly at the barrier support post's surroundings by a board simulating a vehicle of 1000 kg mass, moving with velocity of 50 km/h.

Steel Sleeve Numerical Analysis with a Supplementary Energy-Absorbing Element

The obtained results of deformation analysis for the second model of the post, with the supplementary energy-absorbing element, are presented in Figures 18 to 20. The composite sleeve deformation energy is shown in Figure 16, which shows that the energy increase was linear (until the vehicle loses its kinetic energy).

As the result of the second model calculations, it was found that the maximum strain deformation energy for post was 3000 J, and the maximum composite sleeve strain deformation energy was 14 J. This means that it is purposeful to apply in the real object a belt of such sleeves with complementary profiled interior completed with e.g. metallic foam. The kinetic energy of the analysed system shown in Figure 17 reaches the maximum value equals 40 kJ.

The Figures 18-20 present the results in contour form for chosen moments. For 1,4e-5 s. (Figure 18), it was observed that the composite sleeve deformation is equable. The maximum displacement of sleeve nodes was 0.0115 m.

Figures 19 and 20 present the successive results of the analysis process. The maximum displacement of sleeve nodes was 46 mm. For the total sleeve height of 50 mm, its deformation is about 80%. Figure 20 presents the last step of the calculations. During the estimation of sleeve deformation form it was observed that, like in the experiment, the composite sleeve was deformed in an equable way. Particular importance should be paid on the form of composite element deformation obtained in the result of simulation process.

The rapid increase of the compression force was due to contact of the board and the post. The very interestic is the problem of EK [kinetic energy] increase of the sleeve, presented in Figure 17. This energy increased equably during the compression test of the energy-absorbing element.

CONCLUSIONS

The study presented offers an experimental and numerical analysis of energy-absorbing element in a form of composite sleeve. On the basis of an experiments performed in the first part of the study, the numerical analysis of the steel road barrier (first model) was investigated, and of the barrier equipped with this supplementary energy-absorbing element (second model). The payload variant assumed during the analysis was the one in which the vehicle modelled by the rigid board crashes the post perpendicularly with velocity 50 km/h.

As a result of the second model numerical calculations it was found that, the maximum post strain energy was 3 kJ. The maximum composite sleeve deformation energy was 7,5 J. It means that is very useful to apply a belt of energy-absorbing elements in form of sleeves with complementary profiled interior completed with e.g. metallic foam, as it was presented in Figure 21. The total impact energy absorption requires the application of a belt of elements made of epoxide composite with glass fibres. Authors are focused to investigate the stiffness' relationships between barrier system elements.

The successive stage of the tests will be the consideration on the existing structure modification, in order to increase its energy-absorption characteristics, by applying the elements with changed profiles and new structures capable to absorb more energy, reinforced additionally with metallic foams. The selected cases of numerical models will be verified experimentally, which will allow for a reliable and complex durability analysis of all the energy-absorbing barriers during the crash. The method proposed, based on numerical tests, will allow for elimination of expensive and time-consuming tests of the real objects. The results obtained will be applied as guidelines during the researches of such type of structures, and possibly utilized in the successive investigations.

ACKNOWLEDGEMENT

The research was carried out under a research grant 4 T12C 060 26 from the Polish Committee for Scientific Research. This support is gratefully acknowledged.

REFERENCES

[1] Niezgoda T., Barnat W. Analysis of protective structures made of various composite materials subjected to impact , Materials Science and Engineering A, MSA22822 1–3, article in press.

[2] Ochelski S. Metody doswiadczalne mechaniki kompozytow konstrukcyjnych. WNT, Poland, 2004.

[3] Meguid SA, Stranart JC, Heyerman J. On the layered micromechanical three-dimensional finite element modelling of foam-filled columns. Finite Elements in Analysis and Design, 2004;**40**: 1035–1057.

[4] Farley GL, Jones RM. Energy absorption capability of composite tubes and beams. NASA TM-101634, AVSCOM TR-89-B-003, 1989.

[5] Sahid I, Fu-Kuo Ch. An accumulative damage model for tensile and shear failures of laminated composite plates. Journal of Composite Materials, 1995; **7**: 926-981.

[6] Hull D. Energy absorption of composite materials under crash conditions. Progress in Science and Engineering of Composites-Proceedingsof ICCM IV, Pergamon Press, 1982; pp. 861-870.

[7] Farley GL. The effect of fiber and marix maximum strain on the energy absorption capability of composite materials. Journal of Composite Materials, 1986; **20**: 322-334.

[8] MSC Dytran Example Problem Manual, Version 3.0 MSC 1996,

[9] Hull D. A unified approach to progressive crushing of fibre-reinforced composite tubes. Composites Science & Technology, 1991; **40**: 377-421.

[10] Thornton PH, Edwards PJ. Energy absorption in composite tubes. Journal of Composite Materials, 1982; **16**: 521-545.

[11] Rajbhandari SP. An approach to modelling and predicting impact damage in composite structures. ICAS 2002 Congress, pp. 862.1 - 862.10.

[12] Fleming DC. Delamination modelling of composites for improved crash analysis. Journal of Composite Materials, 2001; **35**: 1777-1792.

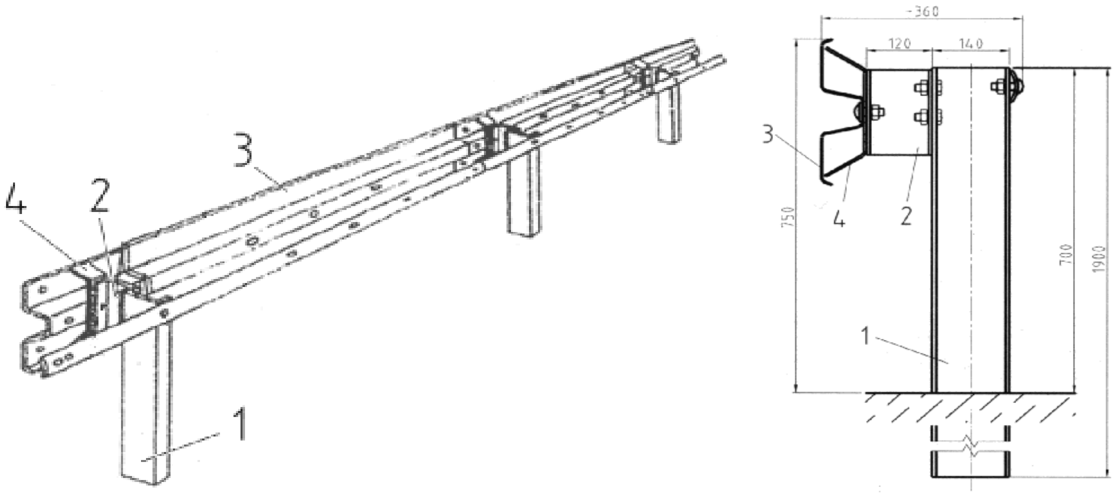

Figure 1: Schematic diagram of a section of a protective road barrier, type SP-06: post (1), separator (2), guide (3), holder (4).

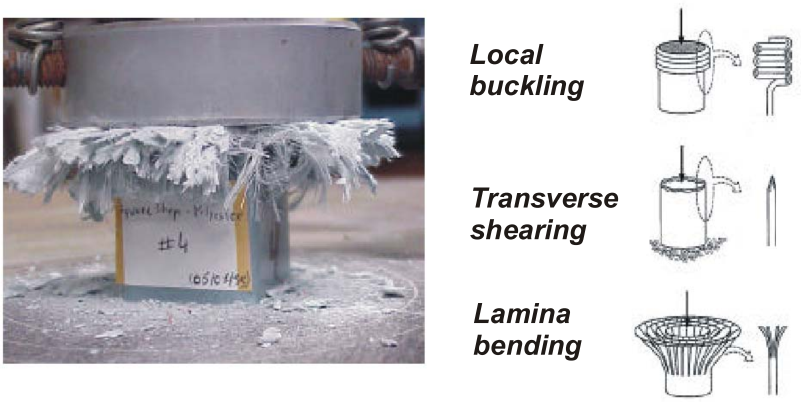

Figure 2: Schematic presentation of three basic forms of composite structure destruction [4].

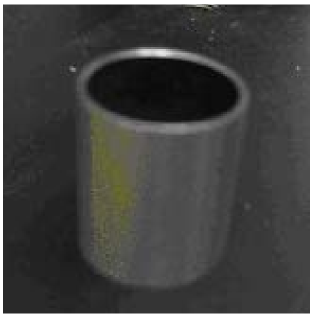

Figure 3: Experimentally tested steel sleeve

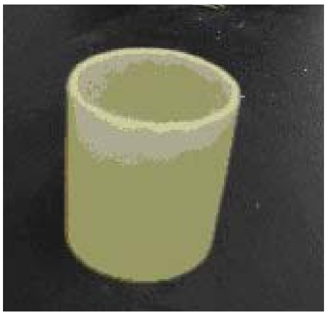

Figure 4: Experimentally tested composite sleeve

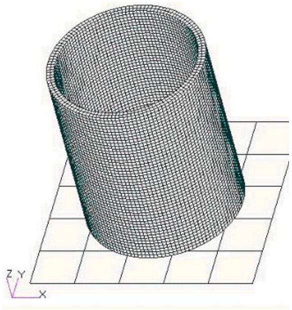

Figure 5: The finite element model of a sleeve

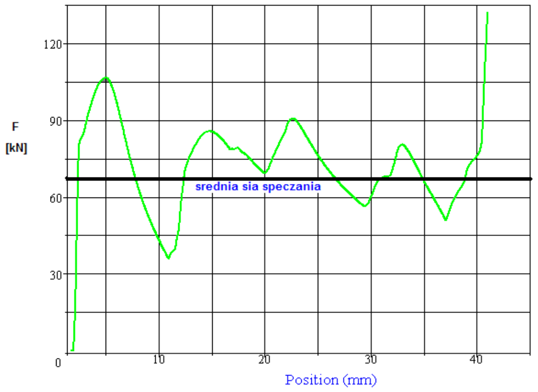

Figure 6: Diagram of compression force from tests of steel sleeve

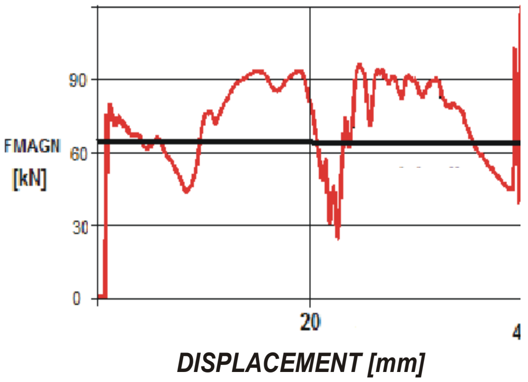

Figure 7: Numerically obtained diagram of compression force

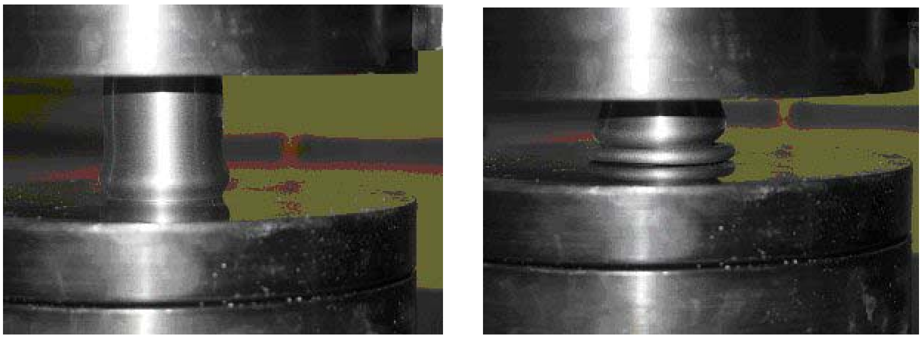

Figure 8: Deformed shape of steel sleeve

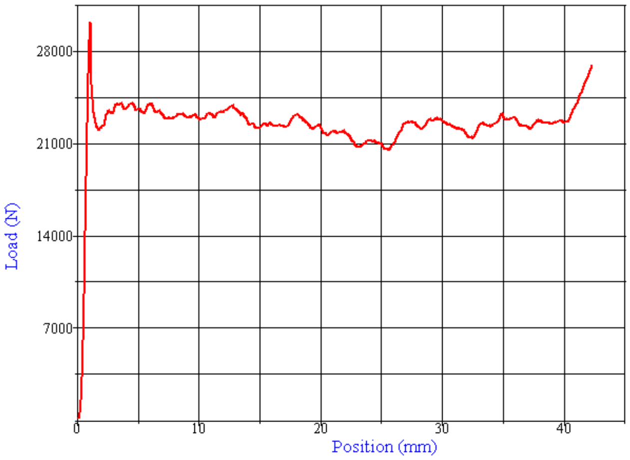

Figure 9: Composite sleeve compression force diagram experimentally obtained.

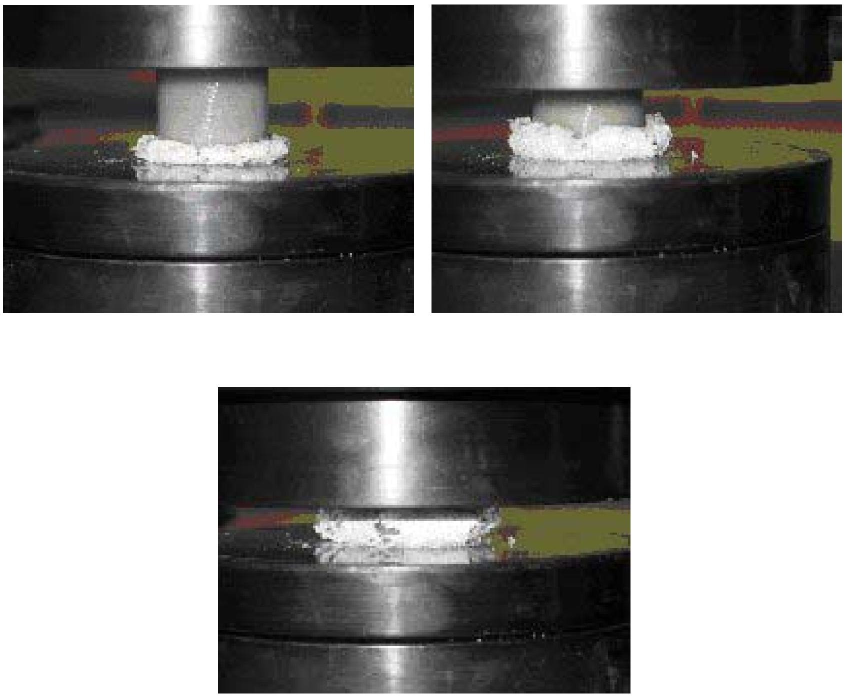

Figure 10: Composite sleeve deformation shape.

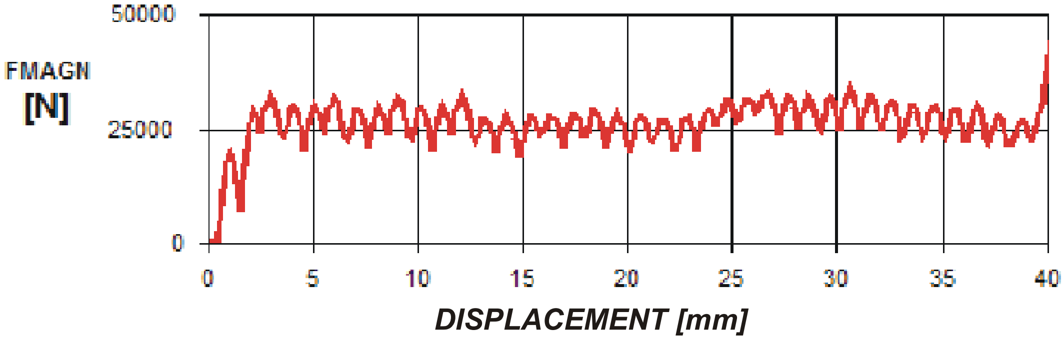

Figure 11: Numerically obtained composite sleeve compression force diagram.

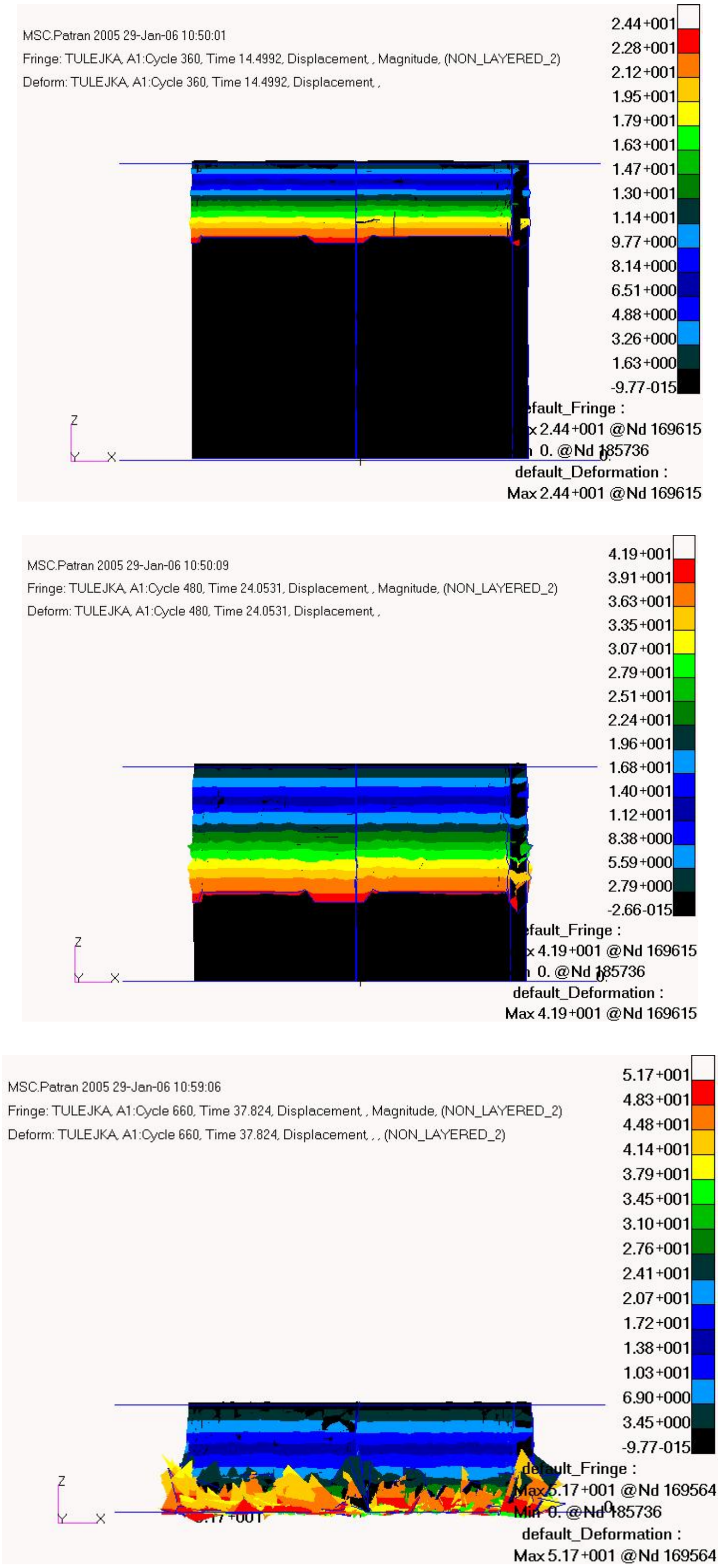

Figure 12: The composite sleeve deformation shape in numerical simulation process of composite sleeve.

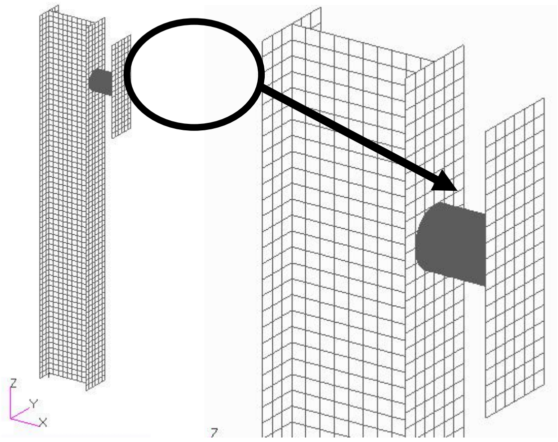

Figure 13: Scheme of the second numerical model of the post with additional energy-absorbing elements.

Figure 14: Scheme of numerical model of the sleeve.

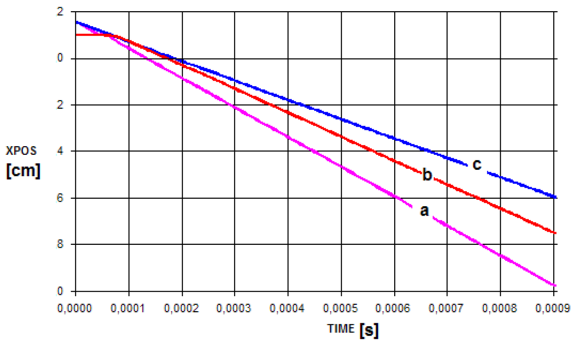

Figure 15: Displacement of nodes on the post:a); on the sleeve: b; on the impact board c.

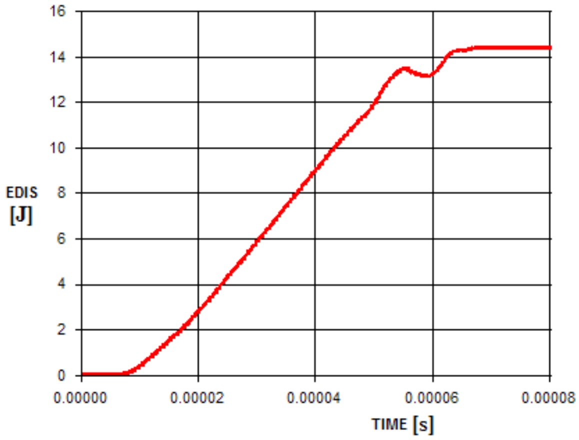

Figure 16: Strain energy diagram for the composite sleeve

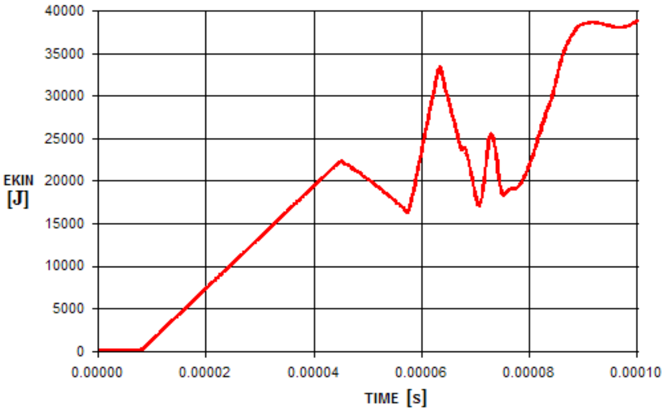

Figure 17: Kinetic energy change diagram for the composite sleeve

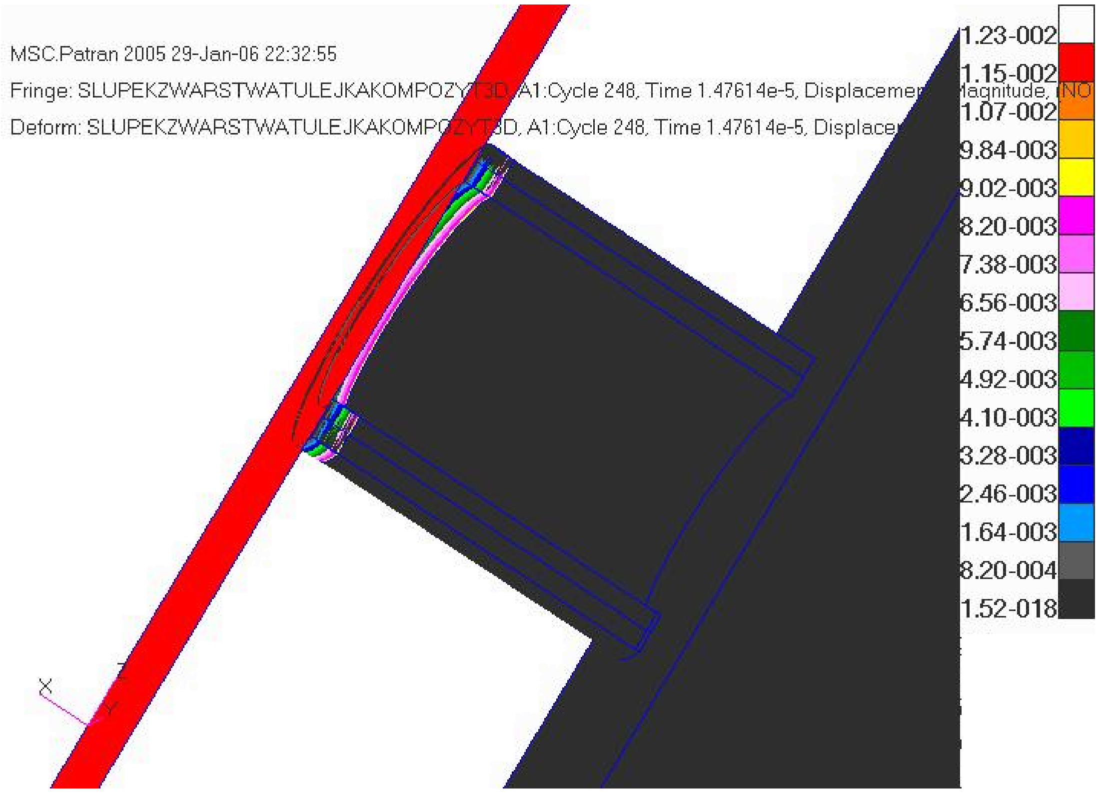

Figure 18: Post deformation map (time 14.7 miks)

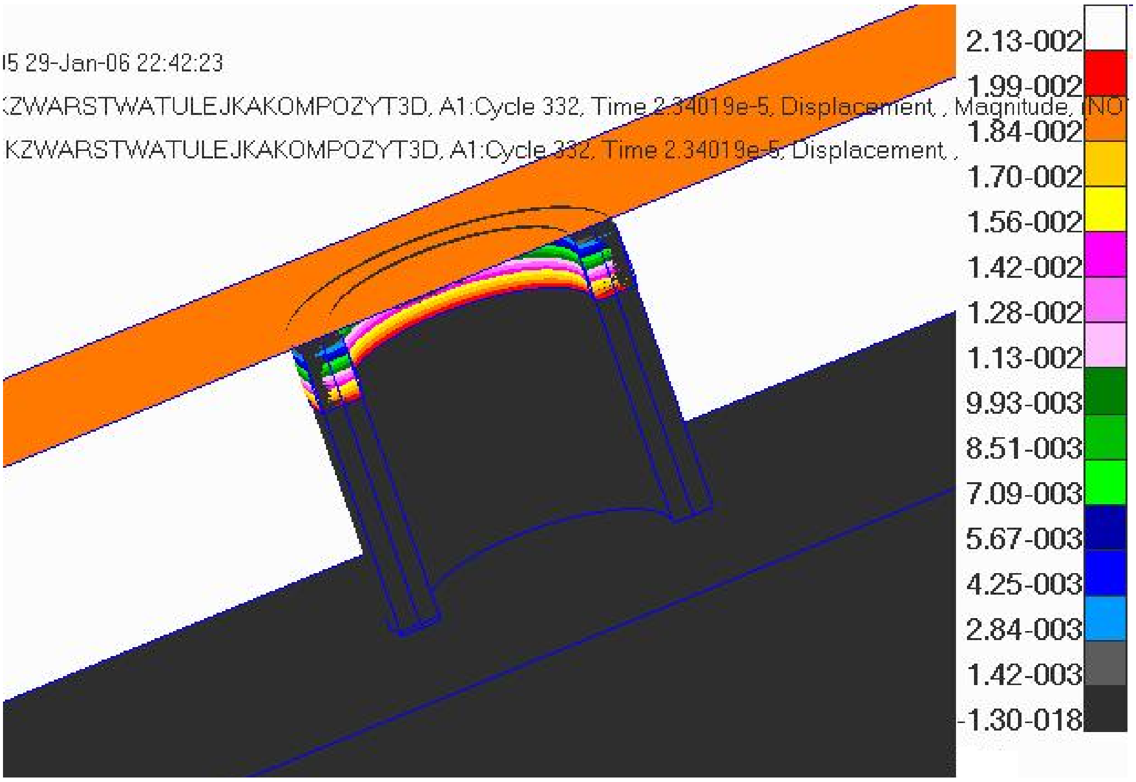

Figure 19: Post deformation map (time 23 miks)

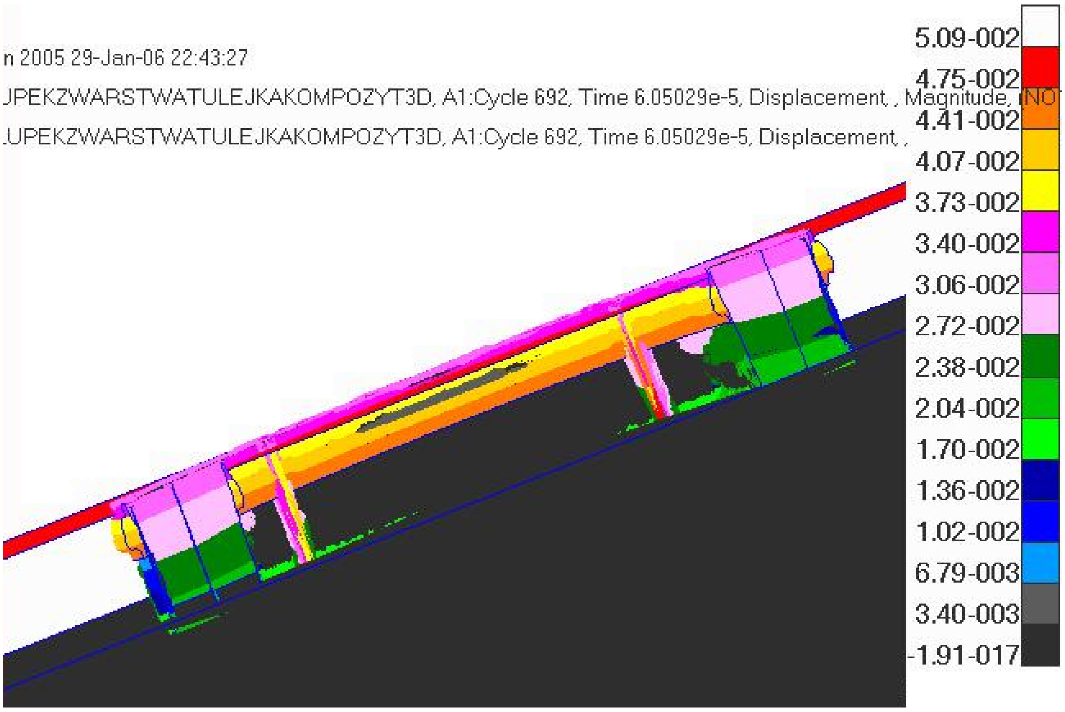

Figure 20: Post deformation map (time 60 mikss)

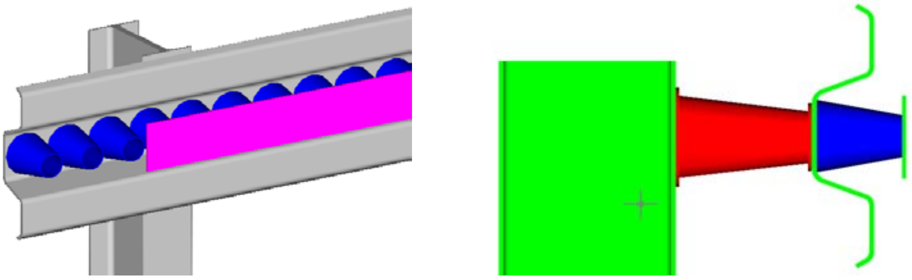

Figure 21: Scheme of the proposed construction solution, improving guide energy-absorbing characteristics