NUMERICAL ANALYSIS OF PROGRESSIVE FAILURE OF COMPOSITE ENERGY ABSORBING STRUCTURES

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Abstract

The aim of the paper was to compare the influence of the applied fill on the energy absorbed by the energy absorbing structural elements made of composite, steel and from composite with fill foam. The experimental tests were carried out on an INSTRON universal testing machine at the speed rate of the machine's traverse equal 10 mm/min and the numerical analysis has been performed using MSC. Dytran software based on the Finite Element Method. The elements were subjected to axial kinematic loads. The higher specific absorbed energy occurs in the case of energy absorbing elements made of composites and from composite with fill foam. These elements can be applied in structures designed for the protection of people or limitation of the whole structure failure, e.g. in the case of a helicopter or car crash etc. The failure progressing in a relatively uniform manner results in the fact that the work used for failure of an energy absorbing element causes a substantial reduction of the impact load results. Application of energy absorbing elements may be a system dissipating the energy of a car impact into a crash barrier. The results of numerical simulation of stiffness plate hitting to the road barrier are presented. Experimental tests and numerical simulations were also presented for a composite sleeve subjected to progressive failure, which allowed carrying out simulation and analysis of a crash into a road barrier protected by a system of two such sleeves.

Keywords: *transport safety, road barriers, numerical analysis, energy-absorbing element, FEM*

1. Introduction

Materials called fibre composites in the course of their approximately 60 years of history had no overwhelming career. Nevertheless, their use in various type structures is systematically, although slowly, growing.

In this paper, phenomena occurring in the course of the progressive failure of composite structures are discussed and the processes responsible for the shock energy absorption are pointed out. Also are presented the most popular techniques, applied for simulating these processes, as well as the authors' own numerical investigations.

2. Phenomena occurring in the course of composite specimens' failure

The failure process of the composite structure at the level of its microstructure consists of:

- failure occurring in a single layer, such as: fibre and matrix cracking, fibre buckling and separation of a fibre from the matrix; it should be added here that the process of separation of fibres from the matrix is not only a mechanical problem, but also a thermal and a chemical one,
- delamination of individual layers.

On the macro scale, all mentioned phenomena can occur simultaneously in different proportion and scale, which is the reason for various global effects.

The experiments carried out by Farley [1], Hull and other researchers [5] show the occurrence of three basic mechanisms of progressive failure of specimens (Fig. 1). They are: local buckling, transverse shearing and lamina bending.

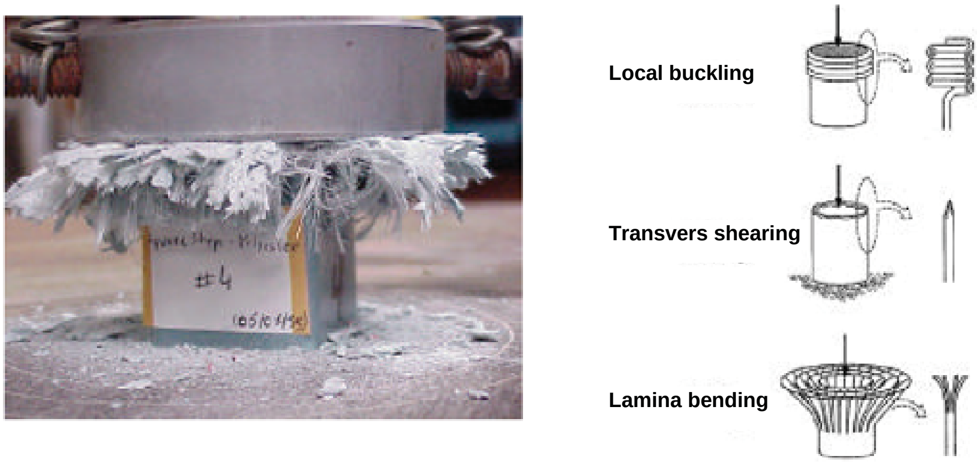

Fig. 1. Schematic presentation of three basic failure modes of composite structures [5]

Failure through progressive transverse shear occurs in composites, in which the reinforcement is made of brittle materials (graphite). The edges of failed specimens take on a characteristic, wedge shape. The inter-layer cracks cause breaking-off of successive parts of the specimen's material. In this case, this breaking-off mechanism of successive parts of the material is mainly responsible for the absorption of energy.

The lamina bending is characterised by formation of very long inter-layer and intra-layer cracks, as well as cracks parallel to the fibres.

Those cracks cause separation of individual layers and even single strips of material. In contrast to the case of transverse shearing, the individual fragments of the specimen do not break but undergo further bending. In the end, a characteristic ,,brush" is formed.

A sudden and catastrophic scenario of failure is also possible. In this case, the absorption of energy does not actually take place and the failure process itself is very violent. Such a situation happens if the structure is subjected to a load considerably exceeding the structure's strength or if one of the above described mechanisms responsible for progressive failure is blocked.

3. Simulation of composite failure using FEM – typical techniques

The attempts undertaken so far at developing algorithms enabling simulation of the progressive failure of a composite, from the viewpoint of the representation of the composite in the FEM model, can be divided into two main trends:

- approaches consisting in finding a criterion possible to implement with the help of various parameters modified in the course of computation (setting to zero the shells thickness, degradation of stiffness),
- approaches in which failure is modelled by methods similar to those used in Fracture Mechanics: layers of the composite are joined by various type links, which – after fulfilling specified criteria – are eliminated.

3.1. Modelling of individual layers of the composite

Representation of a single layer of the composite in the discussed approach must reproduce the behaviour of reinforcement at tension, compression and bending. The criteria applied here are those well known from the ,,classical theory of composites", i.e. maximum allowable and square strain in the stress space. Into the latter group belong Tsai-Hill and Tsai-Wu criteria, which act as indicators (if stress inside the element fulfils the failure criterion, the element is ,,switched off" – its stiffness takes on value close to zero) or the criteria ,,distinguishing causes of failure" as Hashin or Chang ones. In the case of the latter ones, failure may occur after fulfilling one of several criteria defined in a form of independent equations.

Hill and Tsai models only point out the failed layer but do not give any information on the failure mode that has occurred. In the MSC.Dytran programme there are 5 failure modes available coming from: fibre tension (FT), fibre compression (FC), matrix tension (MT), matrix compression (MC) and matrix shear (MS). The programme enables also a combination of these modes. For a more sophisticated model, for which it is impossible to match the earlier mentioned options, one can use the integration method alternative to CLT.

The Hashin model, used for computation in the MSC/DYTRAN [11] programme, takes into account only tension and compression of fibres, as well as tension and compression of the matrix. The failure equations for the tension case take the form:

$$\begin{cases} \text{Fibre tension:} & \left(\dfrac{\sigma_1}{X_T}\right)^2 + \left(\dfrac{\tau_2}{S_A}\right)^2 = 1 & (\sigma_1 > 0) \\ \text{Fibre compression:} & |\sigma_1| = X_C & (\sigma_1 < 0) \\ \text{Matrix tension:} & \left(\dfrac{\sigma_2}{Y_T}\right)^2 + \left(\dfrac{\tau_{12}}{S_A}\right)^2 = 1 & (\sigma_2 > 0) \\ \text{Matrix compression:} & \left(\dfrac{\sigma_2}{2S_T}\right)^2 + \left[\left(\dfrac{Y_C}{2S_T}\right)^2 - 1\right]\dfrac{\sigma_2}{Y_C} + \left(\dfrac{\tau_{12}}{S_A}\right)^2 = 1 & (\sigma_2 < 0) \end{cases}, \tag{3.1}$$

where:

σ_{xx}, σ_{yy} - nominal stress in *x* and *y* directions,

X_C, X_T - maximum (failure) stresses in the fibres (tensile and compressive) in direction 1,

Y_C, Y_T - maximum (failure) stresses in the fibres (tensile and compressive) in direction 2,

S_T - maximum value of transverse shear,

S_A - shear stress in the layer's plane.

In the Hashin model the matrix can be treated in two ways:

- it may be not represented by finite elements,
- it can be represented as solid elements.

In the first case, the model of the layered composite is made of several shells apart from one another by a single layer's thickness. A large problem connected with this technique is correct modelling of the composite's transverse stiffness. FEM model reveals in this case a tendency to react to transverse loading rather like a pack of thin foils than a homogenous structure of defined thickness. Apart from this, the distorted stresses resulting from transverse shear may be cause of improper calculation of the above-mentioned failure criteria (Fig. 2).

Modelling the resin using 3D elements raises less doubt of theoretical nature but can lead do models of a very large number of elements. One can say that at the current state of available computer technology we exchange in this way a part of problems from the field of mechanics for problems from the field of computer science.

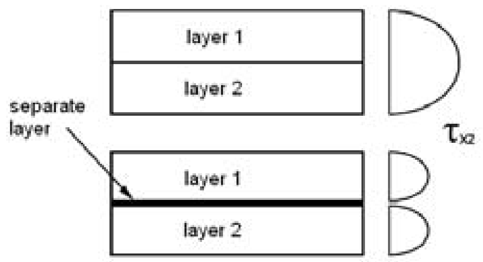

Fig. 2. Distribution of shear stresses in the real composite (upper part) and in the composite modelled by two separate shells (lower part)

3.2. Modelling of delamination

As it was mentioned earlier, attempts have been made to account for delamination through introduction of various type parameters into the homogenous models (i.e. with no physical division into layers) or through application of various criteria for the loss of continuity in models, where each layer of finite elements represents a layer of the composite. Described below are the most popular techniques belonging to the second category, based on the theory of crack formation and propagation.

3.2.1. Virtual Crack Closure Technique (VCCT)

Examples of application of this technique, originating from the Fracture Mechanic, can be found in [5] and [7]. In the FEM model each layer of the composite is modelled. In the course of analysis, deformation energy and failure criterion are checked for each link. The algorithm presented below, used in [5], is very representative for this approach:

- check if a given link is located at the crack front,
- define directions K_I, K_{II} and K_{III},
- calculate energy release rate,
- check the crack criterion,
- if the criterion is fulfilled (i.e. decohesion takes place), the link's stiffness is reduced.

The components of the energy release rate are calculated using VCCT. E.g. for mode I the following formula is used:

$$G_I \approx \frac{1}{2\Delta a} F_I (u^+ - u^-), \tag{3.2}$$

where:

F_I - force acting in the link in the direction corresponding to K_I,

u^+, u^- - displacement of nodes located at the crack front in the K_I direction,

Δa - value depending on the elements' size (increase of crack length).

In the discussed example the crack criterion has the following form:

$$\frac{G_I}{G_{Ic}} + \frac{G_{II}}{G_{IIc}} + \frac{G_{III}}{G_{IIIc}} = 1. \tag{3.3}$$

The advantages of the presented method include established theoretical foundations and a wide range of publications. The method's disadvantage consists in dependence of the results on the finite element mesh density.

3.2.2. Decohesive model

In this method, as previously, individual layers of elements representing layers of the composite are joined by links. The difference consists in the definition of the link, called also connector. It is assumed in the decohesion model that the connector has a characteristic shown in Fig. 3. A more detailed explanation of physical backgrounds of this approach can be found in [8].

Part of the area under the curve (from U_{kryt} to U_{max}) corresponds to the energy release rate. U_j is the relative displacement of the connectors ends.

In comparison with the „spot-weld" method, described further in, this model has the advantage of taking into account the dissipation of energy during delamination. Examples of application of the decohesive model can be found in [10].

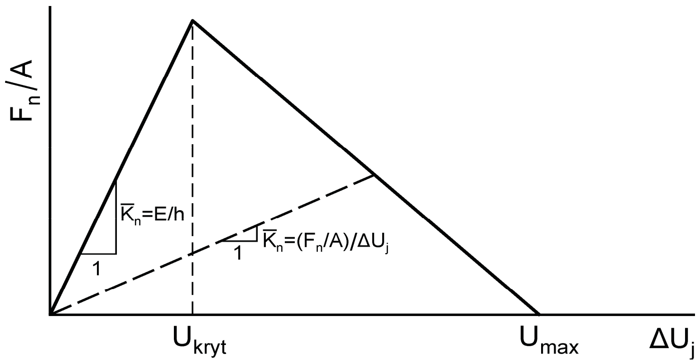

Fig. 3. Characteristics of the connector in the decohesive model

3.2.3. „Spot-weld" type approach

In this case, separable kinematic constraints are used as connection between the layers. From the three described methods of delamination, this one is the easiest in application, because majority of programmes used in the crash type analysis are equipped with elements of this kind.

Separation of nodes takes place after fulfilling definite conditions. Usually we have at our disposal criteria based on the forces acting in the connecting element or – more rarely – on the stresses occurring in the connected elements. Particularly the latter tool may be worth noticing because it makes the delamination process independent of the element size. On the other hand, though, such a technique does not take into account the fact of energy absorption by the delamination process.

Nevertheless, examples are known of arriving at a good enough correlation between the experimental data and the results of numerical computations for real problems, obtained using this method (c.f. [10]).

4. Exemplary calculations

4.1. Model with decohesive elements

The method presented in the preceding chapter was applied for a model of a conic specimen subjected to crash load of axial compression. The model of the cone (its half) is shown in Fig. 4.

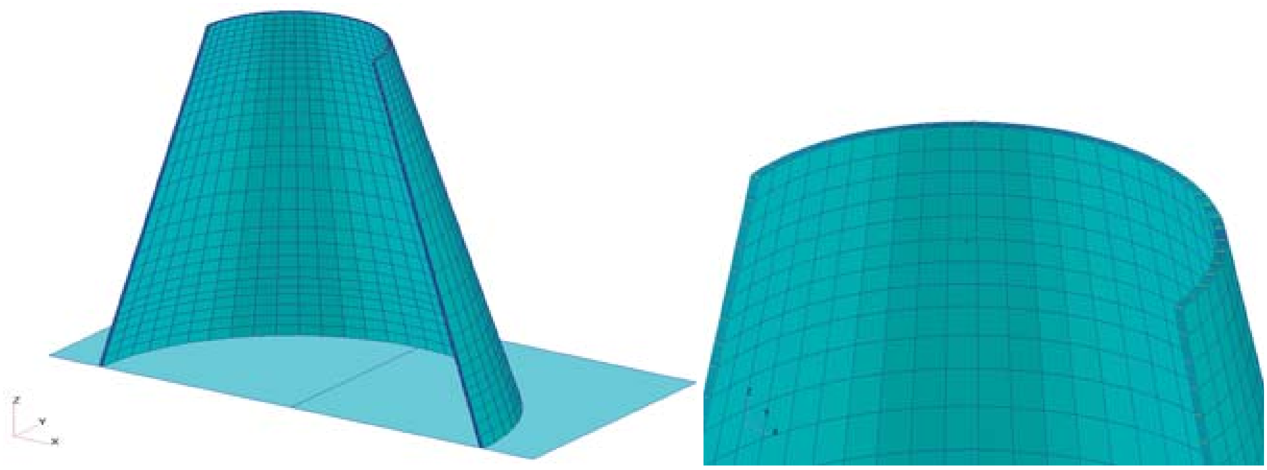

Fig. 4. Cone model

The cone's height is 100 mm; its diameter at the bottom 95 mm; diameter at the top 50 mm; wall thickness is constant and amounts 1 mm. The loading is a stiff flat plate (not shown in the figure) falling down onto the structure along the z axis. The mass of the plate is 100 kg and its initial velocity is 2.0 m/s. The models consisted of 5 layers of the composite represented as separate shells. The connectors were springs (acting in the direction „from node to node") with „energy absorption" characteristics corresponding to those of epoxy resin given in literature (F_{max}, $\Delta x(F_{max})$). In series 2, apart from springs, additional beam elements with a high moment of inertia and a very low longitudinal load capacity were used. The spring characteristics are presented in Fig. 5.

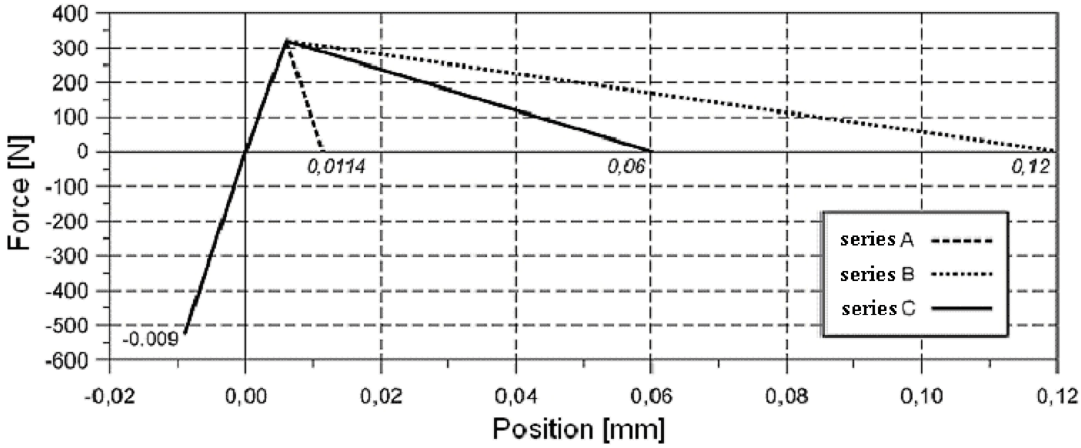

Fig. 5. Characteristics of the springs used to model decohesion

Typical form of deformation is shown in Fig. 6. The vertical cross section of the cone and its shape before deformation are visible. During failure, the structure took on a „local buckling" – type mode. It is worth noticing that the deformation is not symmetric despite symmetry of the model itself and its loading. The shape of folds, typical for the „local buckling" mode, suggests also that the level of discretisation of the crush zone is not sufficient, and because of that the deformation mode was limited by too large a size of finite elements.

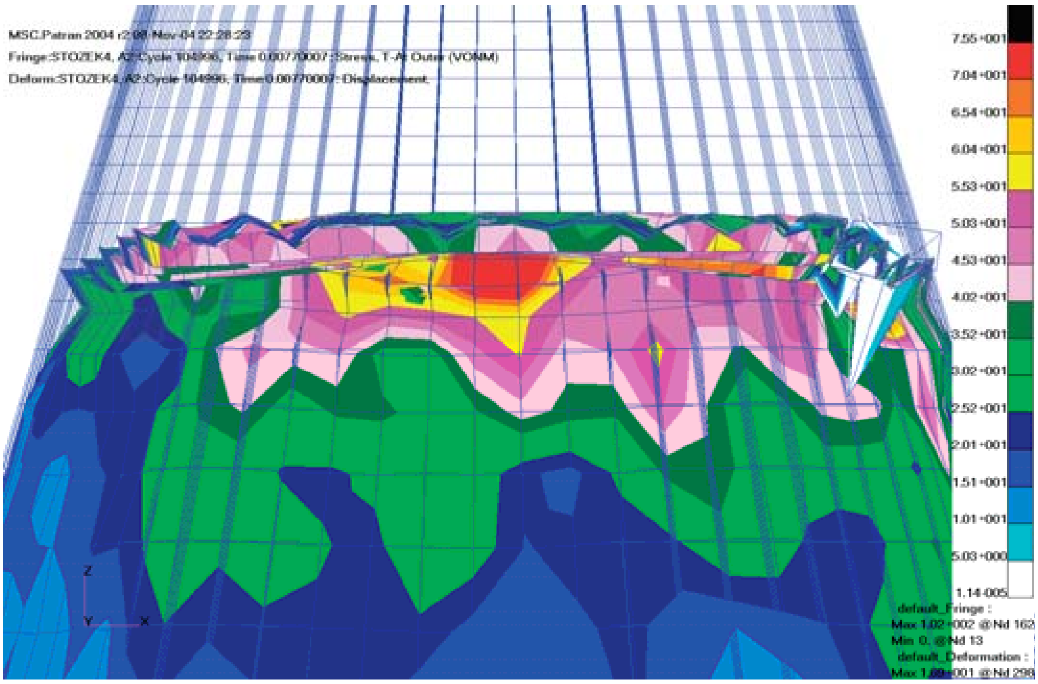

Fig. 6. Typical form of deformation obtained for shell models connected with elastic elements

Results obtained for different properties of the springs are shown in Fig. 7. For comparison, are presented in the diagram results for a FEM model of the same structure made of steel. As a standard, determining the energy absorption capability, the kinetic energy of the attacking body was assumed. It can be seen that the steel cone absorbed the whole crash energy. Model in which the layers were connected only with elastic elements reveal, in the initial phase of calculations, properties close to steel, but for the time of 1.3 ms the calculations diverge.

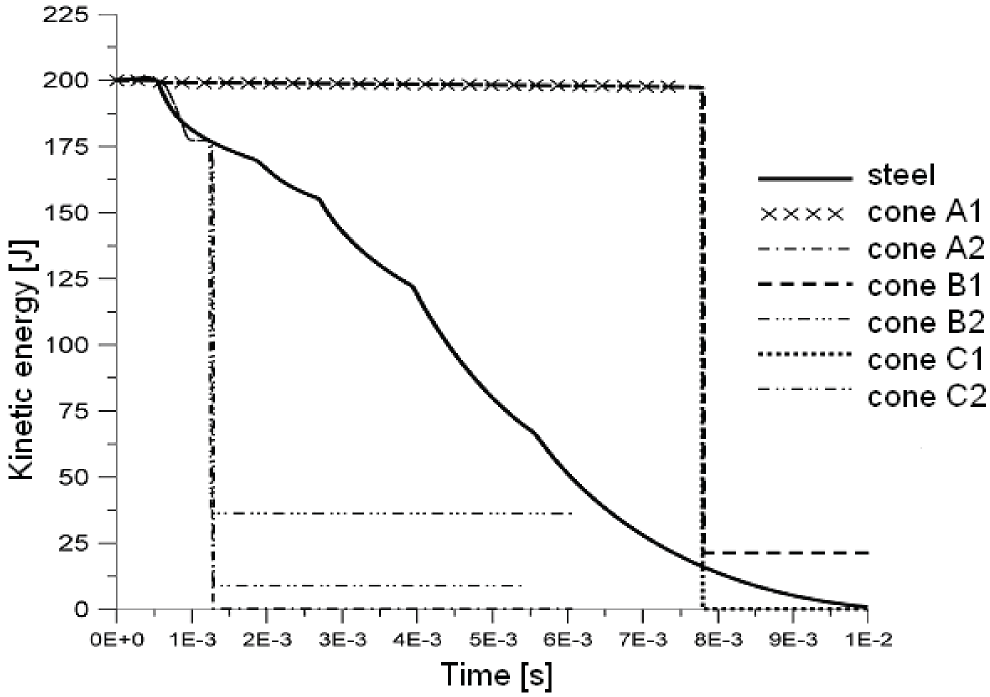

Fig. 7. Diagrams of energy change of the „attacking" body for particular models: Series 1 – models with springs modelling decohesion, Series 2 – models with additional beam elements increasing stiffness in rotational directions

The reason for numerical difficulties was the manner of loading application in the model. It follows from a detailed insight into the analysis that, because the spring nodes were not displacement-driven, the models behave correctly only along the first segment of the load-unload curve, when the force value in the spring was growing with the elongation increase, whereas after attaining the maximum value of the force, the problem becomes indefinite. It means that the described technique can only be applied when the loading is introduced through displacement. As an example of such an analysis can serve the fracture test K_I.

Introduction of additional beams with a small cross section and a high moment of inertia was an attempt to avoid the problems connected with transversal stiffness, described in 3.1 (cf. Fig. 7). As it can be seen from the diagram, the additional beams have the effect of bettering the solution stability. However, they do not eliminate completely the problems with convergence. Surprising enough is the fact that introduction of additional stiffening into the model severely worsened its energy absorption capability. This phenomenon was not analysed, because tests on the models with layers modelled as separate shells were abandoned in favour of the ,,spot-weld" approach.

4.2. „Spot-weld" approach

As mentioned in 3.2.3., one of the ways of modelling delamination is the „spot-weld" method. In order to test this approach, the model used in analyses in 4.1 was modified by adding solid elements simulating the matrix. As a result, a model consisting of 16640 solid and 20808 shell elements was obtained. The shell elements (reinforcement layers) and solid elements (matrix) were connected with BJOIN type ones available in MSC.Dytran. As the failure criterion the values of tensile and compressive forces in the connection were assumed. The model itself is presented in Fig. 8.

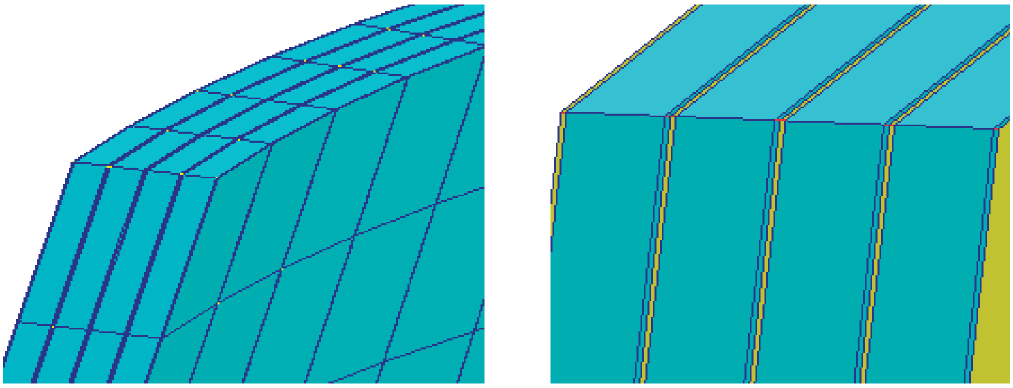

Fig. 8. Details of the model used for testing the „spot-weld" approach

The results of analysis are shown in Fig. 9. This time, we have obtained right away a stable numerical solution with distinct effects of energy absorption. The only problem of numerical nature was a very long time of computations. To obtain the presented diagram it took about 1000 hours (some 41 days) of CPU (Intel Pentium4 2.8 GHz; 2 GB RAM). Moreover, in comparison to purely shell models – data preparation (generation of mesh, connections, definition of contact zones) took much more time.

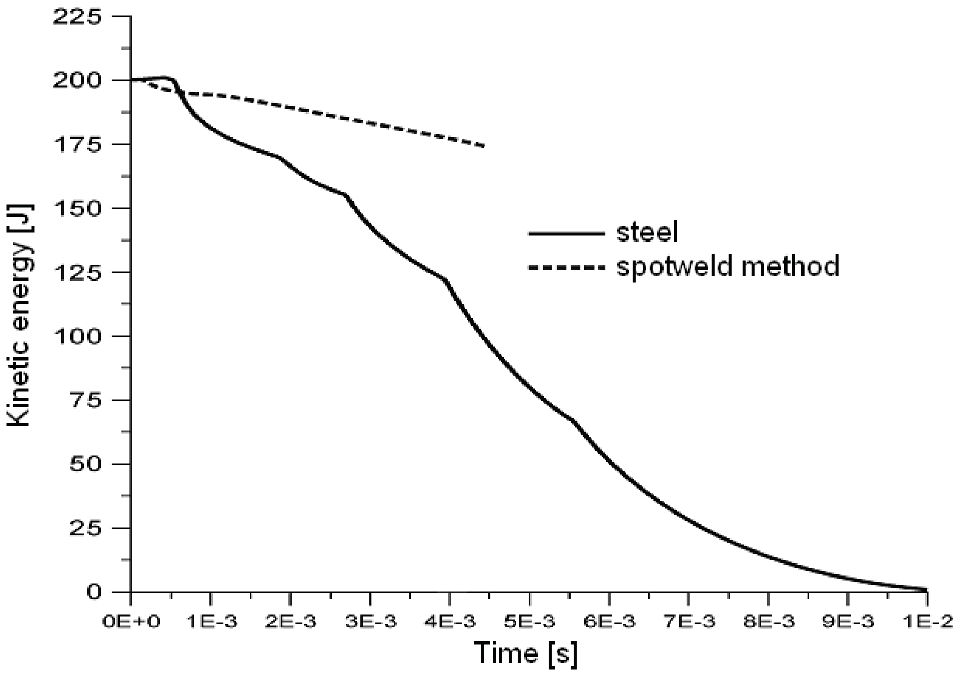

Fig. 9. Energy change diagram of the „attacking" body for particular models

5. Composite sleeve tests

For testing, a composite sleeve shown in Fig. 11 was used. The analysis was carried out using MSC.Dytran software, which is based on the Finite Element Method. Finite element mesh for the numerical model of the sleeve is shown in Fig. 10. In the numerical model the energy absorbing element was made from orthotropic, symmetric glass mat-epoxy resin composite of the following mechanical (obtained from experiment): $E_{1,2}$=6.8 GPa, $\nu_{1,2}$=0.27, $G_{1,2}$=3.8 GPa and geometrical properties (in mm): height 50, internal diameter 40 and wall thickness 2. The mass of the element was 20.7 g. For modelling, SOLID type elements were used. Numerical analysis including large displacements and strains, accounting for geometrical and physical nonlinearity, was carried out. The material model of the composite included the Hashin failure criterion.

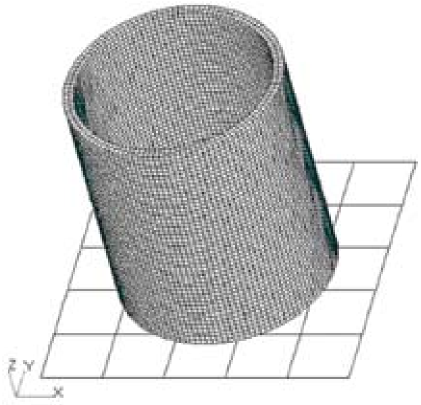

Fig. 10. Finite element mesh for the numerical model of the sleeve

Fig. 11. Photograph of the composite sleeve tested experimentally

As a result of the carried out experiment, a diagram of the crush failure force in dependence of the displacement was obtained. It is shown in Fig. 12.

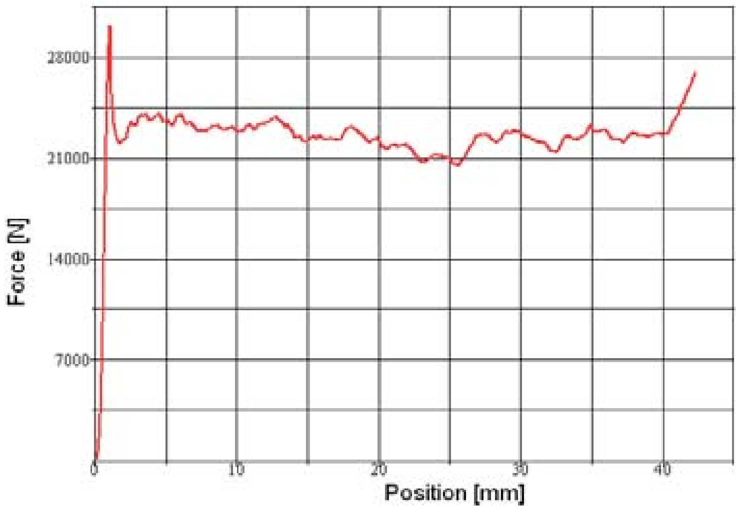

Fig. 12. Experimentally obtained diagram of the crush failure force for the composite sleeve

The plot at its initial stage has a linear character, but the crush failure force attains its maximum value. At this stage, the sleeve under the applied load undergoes no failure yet, and it is not until after attaining the maximum value that the progressive failure is initiated and stabilisation of the force is achieved. The level of the force can be reduced by applying the so called crush initiator (e.g. a bevel at the sleeve's edge). Characteristic for the progressive failure is the deformation mode of the composite sleeve in a shape of delamination (so called „brush effect").

The deformation mode of the composite sleeve is presented in Fig. 13.

Fig. 13. Deformation of the composite sleeve

As a result of the experiment, it was found that the mean value of the crush failure force is 23 kN. After taking into consideration the distance covered by the testing machine's jaws the work of the crush failure force was estimated at 1.125 kJ. Further, taking into account the mass of the tested element, it was found that the specific absorbed energy was 50 kJ/kg.

The above case was also subject to numerical analysis. Similarly as in the former case, the simulation process took into account the conditions of the experiment. As a result of the carried out calculations, the crush failure force diagram versus time was obtained. It is presented in Fig. 14.

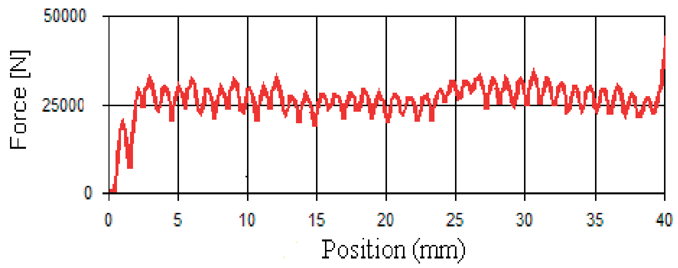

Fig. 14. Diagram of the crush failure force for the composite sleeve, obtained numerically

The deformation mode of the composite sleeve in the process of numerical simulation is shown in Fig. 15.

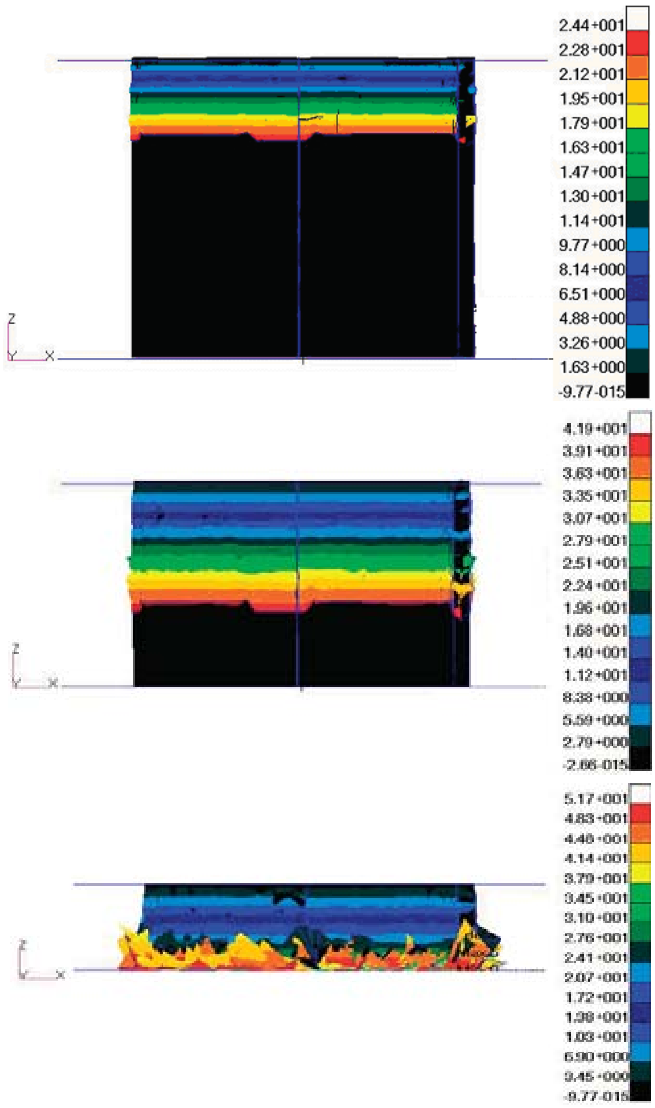

Fig. 15. Deformation mode of the composite sleeve in the process of numerical simulation

Results of numerical calculations show that for the mean value of the crush failure force the specific absorbed energy was about 51 kJ/kg, which agrees well with the value obtained experimentally.

Also were carried out simulation and analysis of a crash into a road barrier post protected by a system of two such composite sleeves, shown in Fig. 16.

a) b)

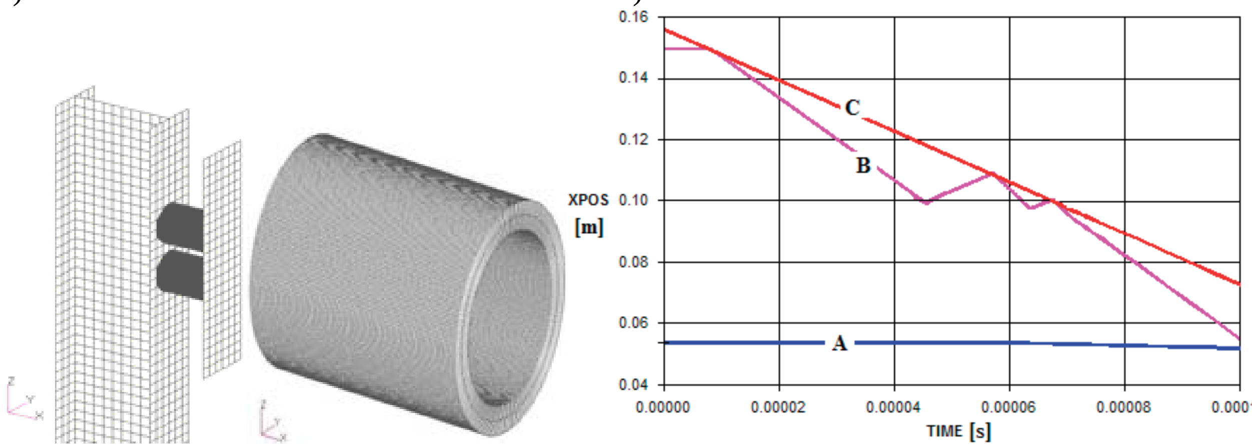

Fig. 16. a) Scheme of the numerical model of a road barrier post with complementary energy-absorbing elements b) displacement of nodes: A; on the sleeve: B; on the impacting plate C

The maximum value of the crush failure force during the progressive destruction of the sleeve, presented in Fig. 17, was 1 MN. The abrupt increase of the crush failure force was due to contact with the plate and to the impact. The kinetic energy of the sleeve, however, increased evenly during the whole process of progressive destruction of the energy-absorbing element.

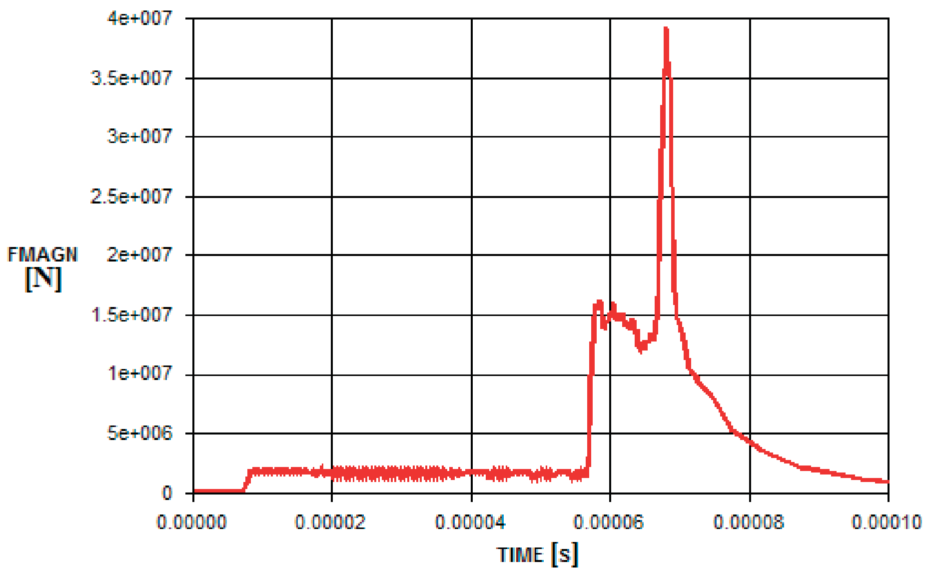

Fig. 17. Crush failure force diagram for the composite sleeve

The Figures 18 and 19 present the successive results of the analysis. The maximum displacement of the sleeve nodes was 46 mm. For the total sleeve height of 50 mm, its deformation reached 80%.

Fig. 20 presents the last step of the calculations. During estimation of the sleeve's deformation form it was observed, like in the case of experiments, that the composite sleeve was deformed in an even manner.

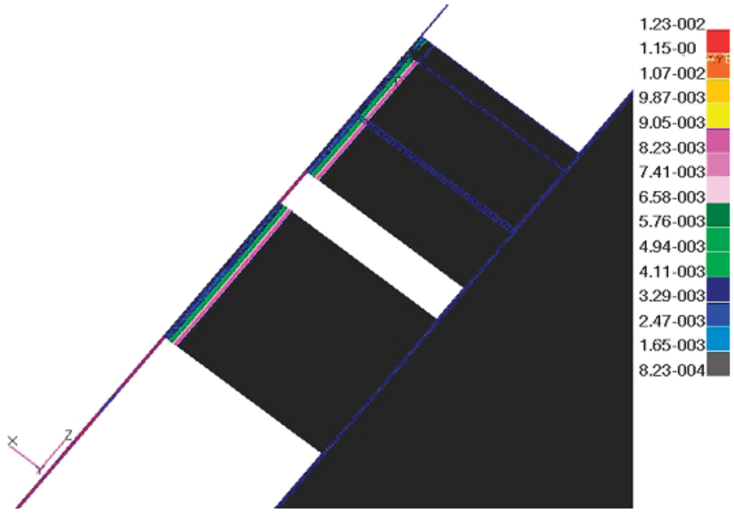

Fig. 18: Road barrier post deformation map for the time of 1.47e-5 s

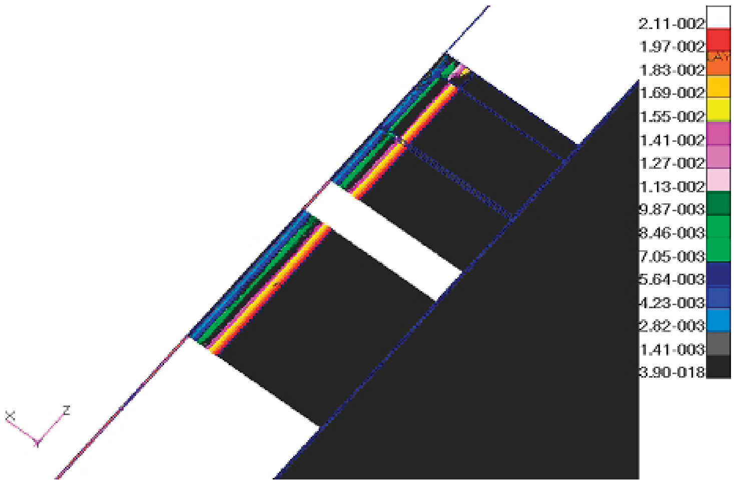

Fig. 19. Road barrier post deformation map for the time of 2.3 e-5 s

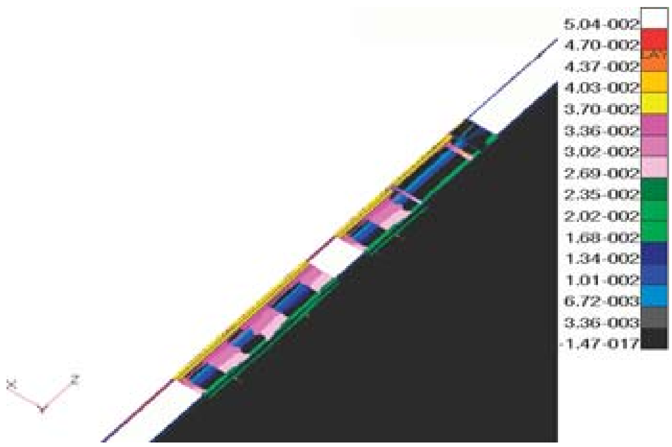

Fig. 20. Road barrier post deformation map for the time of 5.88e-5 s

6. Conclusions

In the paper, phenomena occurring in the course of progressive failure of composites are discussed. The techniques used to describe these phenomena in FEM analysis are presented. It was pointed out that there is a lack of commonly accepted methods and theories allowing obtaining reliable computational results. The numerical tests were carried out using two different methods of modelling the delamination in simulation of a cone–shaped specimen in a crash test. On the basis of the results it was found that the „spot-weld" approach – despite considerable computational power it demands – seems to be more promising for obtaining satisfactory results of simulation. Attempts at applying the decohesive formulation failed due to non-stability of the computational process. It was found that the reason for the convergence problems is the connectors' characteristic, which does not allow to apply this decohesion model in a general computational case.

Experimental tests and numerical simulations were also presented for a composite sleeve subjected to progressive failure, which allowed carrying out simulation and analysis of a crash into a road barrier protected by a system of two such sleeves.

References

[1] Farley, G. R., *Relationship between Mechanical-Property and Energy-Absorption Trends for Composite Tubes*, NASA Technical Paper 3284, 1992.

[2] Rajbhandari, S. P., *An Approach to Modelling and Predicting Impact Damage in Composite Structures*, ICAS 2002 Congress, pp. 862.1-862.10.

[3] Sahid, I., Chang, F. K., *An Accumulative Damage Model for Tensile and Shear Failures of Laminated Composite Plates*, Journal of Composite Materials, Vol. 29, No. 7, pp. 926-981,1995,.

[4] Cananho, P. P., Davila C. G., *Mixed-Mode Decohesion Finite Elements for the Simulation of Delamination in Composite Materials*, NASA/TM-2002-211737, 2002.

[5] Fleming, D. C., *Delamination Modelling of Composites for Improved Crash Analysis*, Journal of Composite Materials, Vol. 35, pp. 1777-1792, 2001.

[6] Paris, F., *A Study of Failure Criteria of Fibrous Composite Materials*, NASA/CR-2001-210661, 2001.

[7] Johnson, A. F., Picket, A., *Impact and Crash Modelling of Composite Structures: A Challenge for Damage Mechanics*, Euro-am'99, 1999.

[8] Reedy, E. D., Mello, F. J., Guess, T. R., *Modelling the Initiation and Growth of Delaminations in Composite Structures*, Journal of Composite Materials, Vol. 31(8), pp. 812-831, 1997.

[9] Chen, J., *Predicting Progressive Delamination of Stiffened Fibre-Composite Panel and Repaired Sandwich Panel by Decohesion Models*, Journal of Thermoplastic Composite Materials, Vol 15, pp. 429-442, 2002.

[10] Fleming, D. C., *Modelling Delamination Growth in Composites using MSC.Dytran*, 2nd MSC Worldwide Automotive Conference – Proceedings, 2000.

[11] MSC.Dytran Theory Manual, version 2005, MSC.Software C.O., 2005.

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