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Numerical analysis of the influence of the blast wave on the composite structure

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1. Introduction

The explosion of high explosive charge, due to a rapid chemical reaction, converts the original charge into gaseous products of extremely high pressure that spread with supersonic speed. Created blast wave properties depend on mass and shape of the charge, material properties of the explosive and surrounding medium. Experimental studies of the blast wave influence on the structures are generally expensive and risky, therefore often computer methods are used instead. Generally, the interaction of blast wave with the structure leads to large deformations, material nonlinearities and sometimes also to failure. From the computational point of view, modeling of the explosion is complex issue, therefore some specific numerical modeling approaches were developed. The most widely used method in modeling of explosion phenomenon is the finite element method (FEM). In this case structure is very frequently discretized by Lagrangian elements while gaseous products of detonation are discretized by Eulerian elements. The influence of the blast wave on structure is modeled as fluid structure interaction problem (FSI) by coupling of Lagrangian and Eulerian domains [1, 2]. Another approach, which is considered during this research, is application of meshless smoothed particle hydrodynamic (SPH) method. In this case detonation products are discretized by particles while structure is modeled by finite elements [3-5]. Particles and finite elements are coupled by the contact procedure.

The paper focuses also on the material modeling problem. Process of designing and optimizing composite material microstructure, volume fraction of phases, phases shape etc. can lead to achieve an unique properties. On the other hand it complicates the mathematical description of material behavior. This is very difficult and could be computationally prohibitive to take into account an exact structure of the material in numerical computations.

Modern composite structures like a sandwich panels with cellular core have a good energy dissipating performance and advantage in weight saving [6], therefore it can be used as an energy absorber under extreme loading conditions in wide range of applications. In presented example energy absorbing sandwich composite panel with honeycomb core was taken into consideration. External face sheets that cover the core are made of metal matrix composite reinforced by particles. The challenge is to apply a proper description of material of the structure subjected to the blast wave influence. Presented approach is based on multiscale modeling idea [7, 8] where the DIGIMAT software is used as a material modeling platform [9]. In the paper the mean field homogenization scheme was used to create homogenous material model that represents real heterogeneous material structure in transient simulation of blast wave affecting energy absorbing panel. The presented simulations were carried out by using LS-DYNA solver based on the explicit time integration scheme.

2. SPH method in modeling of the explosion phenomenon

In the SPH method state of system is represented by a set of particles of prescribed material properties which move according to the equations of conservation of mass, momentum, energy and the equation of state [10]. Mentioned relations are respectively expressed in form of the system of equations:

$$\begin{cases} \dfrac{d\rho}{dt} = -\rho \nabla v; \\ \dfrac{dv}{dt} = -\dfrac{1}{\rho}\nabla p; \\ \dfrac{du}{dt} = -\dfrac{p}{\rho}\nabla v; \\ p = p(\rho, u), \end{cases} \tag{1}$$

where ρ is density, u is internal energy, p is pressure, v is velocity vector and t is time.

One of the most important issue in modeling of explosion phenomenon is application of proper equation of state. The most widely used is Jones-Wilkins-Lee equation [1-5] which scales the pressure of detonation products as follows:

$$p = A\left(1 - \frac{\omega\eta}{R_1}\right)e^{\frac{-R_1}{\eta}} + B\left(1 - \frac{\omega\eta}{R_2}\right)e^{\frac{-R_2}{\eta}} + \omega\eta\rho_0 e\,, \tag{2}$$

where η is ratio of the density of the explosive gas to the initial density of explosive ρ_0, e is the specific internal energy of the high explosive. A, B, R_1, R_2, ω are coefficients obtained by fitting experimental data.

Conception of integral representation of a function $f(x)$ used in SPH method is expressed as:

$$f(x) = \int_\Omega f(x')\,\delta(x - x')\,dx'\,, \tag{3}$$

where f is a function of position vector x, $\delta(x - x')$ is a function given by:

$$\delta\left(x-x^{'}\right)=\begin{cases}1 & x=x' \\ 0 & x\neq x\end{cases}. \tag{4}$$

If the function $\delta\left(x-x^{'}\right)$ is replaced by a smoothing function $W(x-x',h)$, the integral representation of the function *f*(*x*) is expressed as:

$$f\left(x\right)=\int_{\Omega} f\left(x^{'}\right)W(x-x^{'},h)dx', \tag{5}$$

where *h* is the smoothing length.

The smoothing function *W* is defined using the function θ by the relation:

$$W\left(x-x^{'},h\right)=\frac{1}{h^{d}}\theta\left(\frac{\left|x-x'\right|}{h}\right), \tag{6}$$

where *d* is the number of space dimensions.

The most widely used smoothing function is the cubic B-spline [11] which is defined by using θ as:

$$\theta\left(u\right)=C\times\begin{cases}1-\frac{3}{2}u^{2}+\frac{3}{4}u^{3} & dla\, u\leq 1 \\ \frac{1}{4}(2-u)^{3} & 1<dla\, u\leq 1 \\ 0 & dla\, u>2\end{cases}, \tag{7}$$

where *C* is constant connected with the number of space dimensions.

Using the conception of smoothing, spatial derivative $\nabla f\left(x\right)$ of function *f* can be expressed as:

$$\nabla f\left(x\right)=\int_{\Omega}\nabla f\left(x^{'}\right)W\left(x-x^{'},h\right)dx^{'}. \tag{8}$$

The continuous integral representation can be converted to discretized forms of summation over all the particles in the support domain. After replacement of infinitesimal volume *dx'* at the location of particle *j* by finite volume of the particle ΔV_j mass of the particle equals:

$$m_{j}=\Delta V_{j}\rho_{j}. \tag{9}$$

Discretized form of integral representation of function *f*(*x*) and it's spatial derivative $\nabla f\left(x\right)$ is defined as:

$$f\left(x_{i}\right)=\sum_{j=1}^{N}\frac{m_{j}}{\rho_{j}}f(x_{j})W_{ij}; \tag{10}$$

$$\nabla f\left(x_{i}\right)=\sum_{j=1}^{N}\frac{m_{j}}{\rho_{j}}f(x_{j})\nabla W_{ij}, \tag{11}$$

where $W_{ij}=W\left(x_{i}-x_{j},h\right)$.

Finally system of conversation Eq. (1) can be expressed in discretized form with added artificial viscosity Π_{ij} [10]:

$$\begin{cases}\frac{d\rho_{i}}{dt}=\sum_{j=1}^{N}m_{j}(v_{i}-v_{j})\nabla_{i}W_{ij} \\ \frac{dv_{i}}{dt}=-\sum_{j=1}^{N}m_{j}(\frac{p_{i}}{\rho_{i}^{2}}+\frac{p_{j}}{\rho_{j}^{2}}+\Pi_{ij})\nabla_{i}W_{ij} \\ \frac{du_{i}}{dt}=\frac{1}{2}\sum_{j=1}^{N}m_{j}(\frac{p_{i}}{\rho_{i}^{2}}+\frac{p_{j}}{\rho_{j}^{2}}+\Pi_{ij})(v_{i}-v_{j})\nabla_{i}W_{ij}\end{cases} \tag{12}$$

3. Problem description

As the example of presented approach an influence of explosion of spherical charge of TNT on a sandwich structured composite part is investigated. TNT charge of 6.83 kg which is placed 0.5 m from the structure is discretized by SPH particles (Fig. 1). Behaviour of gaseous products of detonation is described by the system of conversation Eq. (12) and Jones-Wilkins-Lee (JWL) equation of state Eq. (2). Considered constants for the JWL equation that are adequate for the TNT are presented in Table 1 [2, 3, 5].

Table 1

TNT constants for the JWL equation of state

ρ_0, kg/m^3	*A*, GPa	*B*, GPa	R_1	R_2	ω	*e*, MJ/kg
1630	371.2	3.23	4.15	0.95	0.3	4.29

The considered energy absorbing sandwich composite structure consists of homogenous aluminium alloy honeycomb core and external face sheets made of aluminium alloy matrix reinforced by SiC particles (Fig. 2, all dimensions are in millimetres). Volume fraction of SiC phase changes gradually over the sheet's thickness from 10% at the bottom to 30% at the top. The honeycomb's profile's wall thickness equals 1.5 mm.

Honeycomb core and face sheets are discredited by shell four node elements. Nodes corresponding to the core and the face sheets are not in coincidence, therefore connection between the core's and the sheet's finite elements is realized by tied contact. Detailed view on the finite element mesh of the honeycomb core is shown in Fig. 3. Considered part is constrained accordingly to Fig. 2. SPH particles are coupled with finite elements by using contact algorithm.

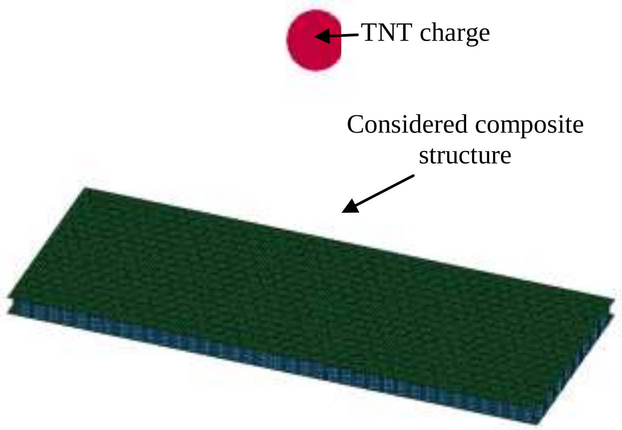


Fig. 1 Discrete model of composite structure and TNT charge

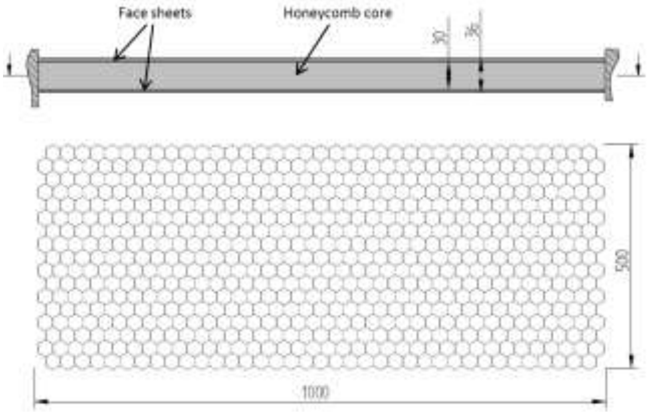


Fig. 2 Considered sandwich composite structure

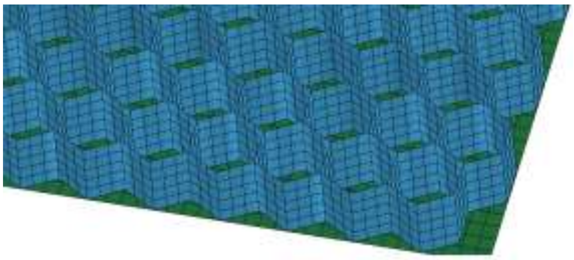


Fig. 3 Finite element mesh of the honeycomb core

4. Material modeling

One of main goals of this paper is also to present the methodology of multi-scale modeling of structure parameters which are further treated as the material model description in numerical simulation of the interaction between blast wave and composite energy absorbing structure. Constitutive behaviour of aluminium alloy is modeled as elasto-viscoplastic using Cowper-Symonds [11, 12] equation which scales the yield stress:

$$\sigma = \left(1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{\frac{1}{p}} \right) \sigma_0 , \qquad (13)$$

where σ is dynamic yield stress, $\dot{\varepsilon}$ is strain rate, σ_0 is initial yield stress, C and p are Cowper-Symonds strain rate parameters.

Material properties used in the simulation are presented in Table 2. As the plasticity model the von Mises hypothesis was used.

In case of aluminium alloy honeycomb core homogenous material model was assumed. Face sheets are made of aluminium alloy matrix composite reinforced with SiC particles. Therefore homogenized effective properties of heterogeneous microstructure have to be determined. In this case essential is application of homogenization procedure which aims to find the effective material properties by analysing behaviour of material on the micro level. Description of material where dependencies between two or more scales are taken into account is connected with conception of multi-scale modelling [7-9].

In the presented simulation effective material properties of considered composite are obtained by application of DIGIMAT-MF software. DIGIMAT-MF is based on the mean field homogenization method [7, 9, 13, 14], particularly in this research Mori-Tanaka scheme [13, 14] is used.

Table 2

Material properties of considered aluminium alloy

Density, kg/m^3	Young Modulus, GPa	Poisson ratio	Yield stress, MPa	Hardening constant, MPa	Hardening exponent	Cowper-Symonds C constant	Cowper-Symonds p constant
2700	70	0.33	275	255	0.3	$1.288{\cdot}10^6$	4

The effective material properties are defined as a function of the matrix and inclusion constitutive relations and inclusion volume fraction and shape. To each phase different constitutive model is assigned. Aluminium alloy matrix is modeled, as stated before, as elasto-viscoplastic material with material parameters presented in Table 2. The SiC inclusion is modeled as linear elastic material with parameters presented in Table 3. Spherical shape of SiC particles are considered.

The effective properties of aluminium alloy matrix composites with different volume fraction of rein -forcement obtained using DIGIMAT are presented in Table 4.

Material properties obtained using DIGIMAT software are transferred to LS-DYNA material card. Besides properties described in Table 4 stress-strain curves are transferred.

Table 3

Material properties of SiC particles

Density, kg/m^3	Young Modulus, GPa	Poisson ratio
3210	450	0.17

Table 4

Effective properties of aluminium alloy matrix composite

SiC reinforcement volume fraction	Density, kg/m^3	Young Modulus, GPa	Poisson ratio	Yield stress, MPa	Cowper-Symonds D constant	Cowper-Symonds p constant
10%	2751	81.59	0.3357	324.4	$1.462{\cdot}10^6$	3.865
20%	2802	95.06	0.3248	361.6	$1.234{\cdot}10^6$	4.152
30%	2853	110.98	0.3135	379.0	$2.255{\cdot}10^6$	4.726

The tensile responses of considered composite material with different volume fraction of the reinforcement are presented in Fig. 4. The influence of strain rate on tensile response of aluminium matrix composite reinforced with 20% SiC particles is shown in Fig. 5.

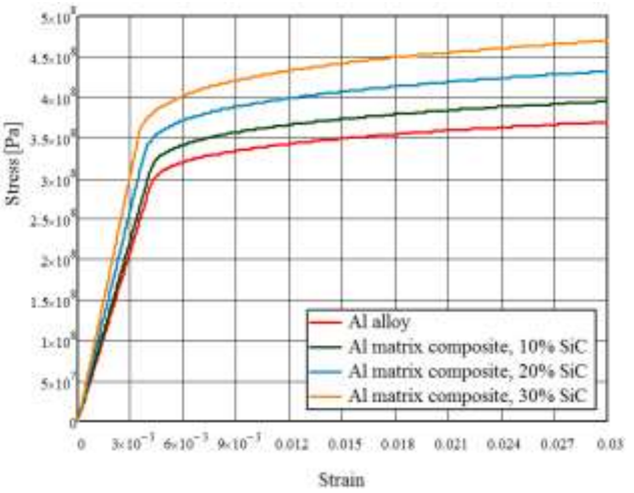


Fig. 4 Stress-strain curves of homogenous aluminium alloy and composites with different volume fraction of reinforcement

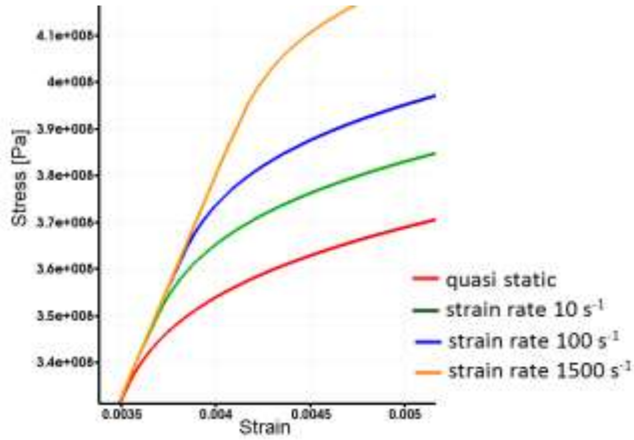


Fig. 5 The influence of strain rate on tensile response of aluminium matrix composite reinforced with 20% SiC particles

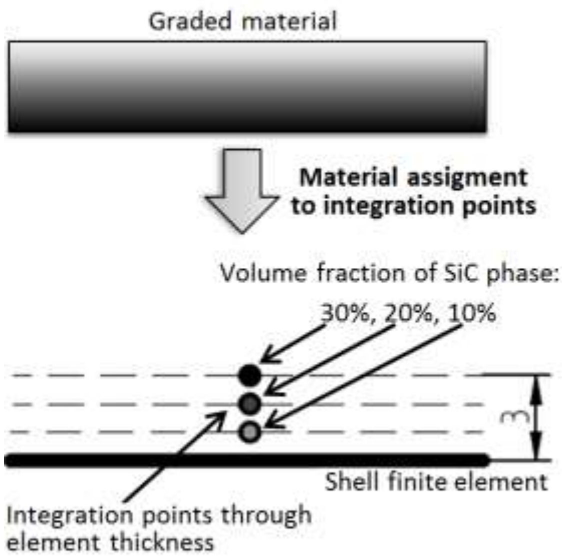


Fig. 6 The modeling of graded sheet metal structure

As stated before, the composite sheets taken into account have graded structure. Variance of face sheet structure was modelled by assigning different material properties to element integration points what is presented in the Fig. 6.

5. Finite element simulation results

Presented figures shows the results of carried out numerical simulations. Fig. 7 shows displacement field of SPH particles, that represent the gaseous products of detonation, 0.0001 s after the detonation of charge. Fig. 8 presents displacement of node located in the centre of the top sheet in function of time.

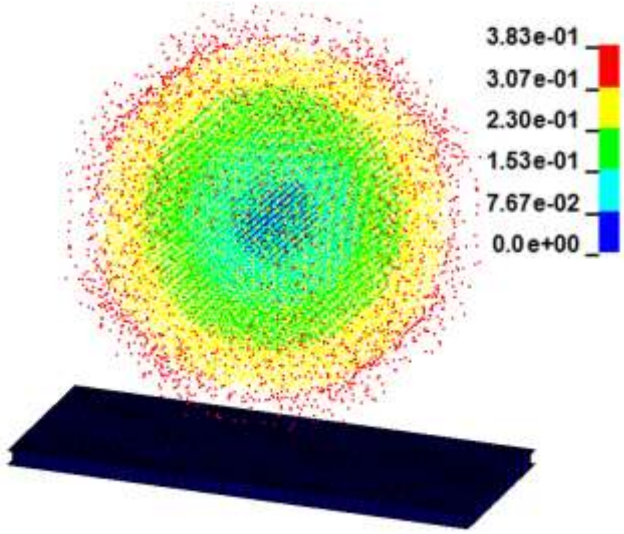


Fig. 7 The displacement field [mm] of SPH particles at time t = 0.0001 s after detonation of charge

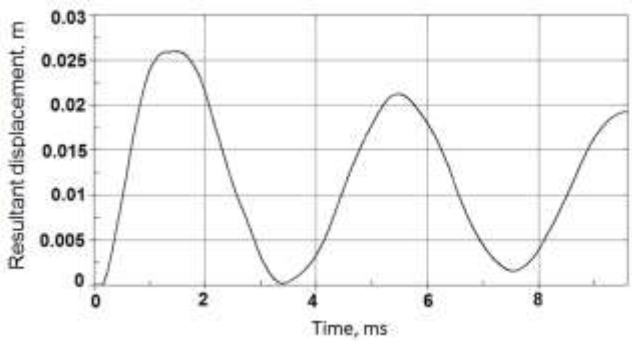


Fig. 8 The displacement of node located in the centre of the top sheet in function of time

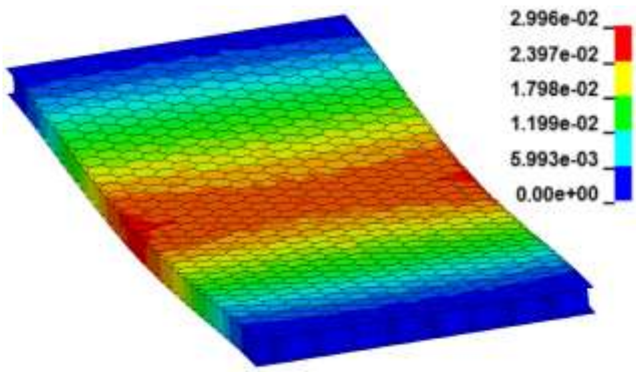
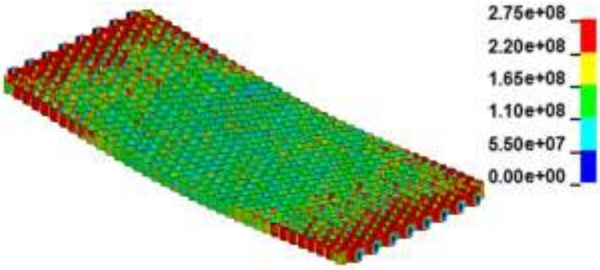


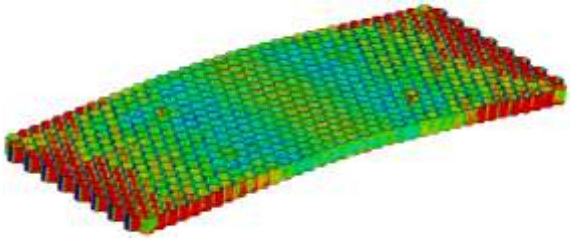
Fig. 9 The displacement field [m] at time connected with the greatest structure's deflection

Results of the influence of the blast wave on the multi-scale modeled composite structure are presented in the form of colours maps of displacement and plastic strain fields. The displacement field is presented in Fig. 9. The von Mises stress field in honeycomb core is presented in Fig. 10.

Obtained plastic strain fields are presented in Fig. 11.

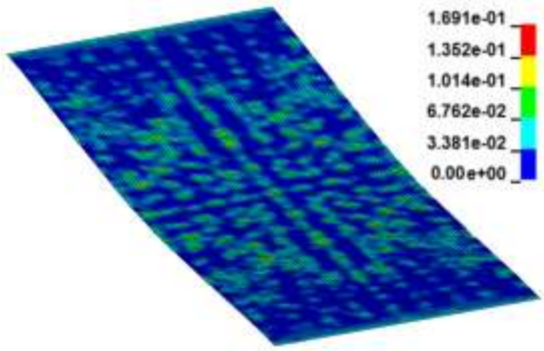


a



b

Fig. 10 The von Mises stress field, Pa in the composite's core at time connected with the greatest structure's deflection (red colour indicates exceeding the static yield stress value): a) top view; b) bottom view



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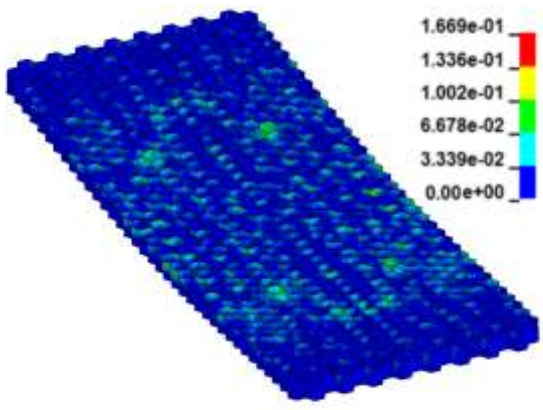

b

Fig. 11 The plastic strain in: a) the top face sheet; b) the honeycomb core

Presented approach could extend the possibilities of optimal designing of the energy absorbing structures. Adequate procedures may lead to find an optimal structure's topology or combination of material parameters at micro level. There are researches conducted on the application of the contemporary evolutionary optimization algorithms which avoid typical problems connected with classical optimization methods [15]. The problem of the time consuming calculation can be resolved by using the computational grid what is described in [16]. Combining the presented approach with the evolutionary algorithms and computational grids can lead to creation an efficient optimization tool with capabilities of analysis the energy absorbing structures based on the composite materials, where constitutive models are obtained by the multi-scale material modeling process.

6. Conclusions

The influence of the blast wave on the structure is often simulated using an Lagrangian-Eulerian finite elements coupling technique. The other way, presented in this paper, is the application of meshless SPH method coupled with Lagrangian finite elements. The main advantages of such approach, in comparison with Lagrangian-Eulerian coupling, are: avoiding of discretization of surrounding medium (only charge is discretized), simulation of expansion of the blast wave is not limited to space discretised by Euler elements, shape of the charge can be easily modelled.

In the numerical simulation of the composite structure it is crucial to define material parameters properly and choose the adequate constitutive model. In the paper the multi-scale approach was applied. The parameters of the structure are obtained by using the homogenization procedure which aims to find the effective material properties by analysing behaviour of material on the micro level. Effective material properties of considered composite were obtained by application of DIGIMAT-MF software. Those parameters are treated as the one of the input data to numerical simulation of the influence of the blast wave on the composite structure.

The combination of meshless and Lagrangian approach in the SPH with the multi-scale material modeling methodology avoids the disadvantages of traditional numerical methods in treating large deformations, large inhomogeneity's, tracing free surfaces and defining heterogeneous material properties in the transient explosion process.

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W. Ogierman, G. Kokot

SPROGIMO BANGOS ĮTAKOS KOMPOZICINEI STRUKTŪRAI SKAITMENINĖ ANALIZĖ

R e z i u m ė

Straipsnyje pateikiamas betinklinės vienalyčių dalelių hidrodinamikos (SPH) metodo taikymas sprogimo reiškinio modeliavimui. Kaip pavyzdys pateiktas sprogimo bangos poveikis kompozicinei konstrukcijai. Tiriama kompozicinė struktūra susideda iš aliuminio lydinio korinės šerdies padengtos lakštais pagamintais iš keraminėmis detalėmis sutvirtintos metalinės matricos. Šios sudėtinės konstrukcijos medžiagų savybės randamos pasitelkiant daugiasluoksnių medžiagų modeliavimo techniką. Pateiktame skaitmeniniame modeliavime tampriosios-viskoplastinės sudedamosios medžiagos modelis įvertina deformacijų greičio įtaką.

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NUMERICAL ANALYSIS OF THE INFLUENCE OF THE BLAST WAVE ON THE COMPOSITE STRUCTURE

S u m m a r y

The paper presents an application of the meshless smoothed particle hydrodynamic (SPH) method in modeling of the explosion phenomenon. As the example the influence of blast wave on the composite structure is presented. The considered composite structure consists of the aluminium alloy honeycomb core covered by face sheets made of metal matrix composite reinforced with ceramic particles. The material properties of this complex structure are obtained on the base of the multi-scale material modeling technique. The elasto-viscoplastic constitutive material model including strain rate effects is taken into consideration in the presented numerical simulation.

Keywords: Smoothed particle hydrodynamics (SPH), blast wave propagation, DIGIMAT, sandwich composite structure.

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