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Numerical Simulation of Stress Wave Propagation in Orthotropic Panel and Comparison with Experiment

Numerická simulace šíření napěťových vln v ortotropním panelu a porovnání s experimentem

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The paper is focused on the issue of non-stationary state of stress in a plane thin orthotropic panel and it continues in the previous work [2, 5, 6, 7] that concerned isotropic material. The panel is made up of unidirectional laminae reinforced with Sigrafil fibres. An experimental measurement was carried out during which a glass projectile was shot onto the panel's sides in the plane of the panel, both along and perpendicular to the direction of the fibres. The time response of the impact loading was measured using eight strain-gauges placed on the front surface of the panel. The data collected were compared with the corresponding results from a numerical simulation. This simulation was performed using finite element analysis (FEA) with and without contact of the two respective bodies. The aim of this work is to become more experienced in the phenomenon of stress wave propagation in structures made of composite materials and to prepare the computational model for future incorporation of progressive material damage models.

Keywords

FEA, fiber-reinforced composites, impact, stress wave propagation

Introduction

The phenomenon of stress wave propagation in isotropic homogeneous solids has been well understood for many decades. With the increasing commercial application and demands for the usage of composite materials also the knowledge of the corresponding issue in non-isotropic and non-homogeneous materials has become crucial (see e.g. [1, 3]).

One type of such materials are the fibre-reinforced composite (FRC) materials and also the laminates made thereof. The unidirectional FRC material can be regarded as an orthotropic material from the macroscopic view, i.e., certain homogenization of the fibres and matrix is applied. This is appropriate mainly in simple quasi-static strain analyses and conservative failure analyses but this method fails to be credible when dealing with material damage. An obvious aspect is that the material inhomogeneity (imperfect bonds between fibres and matrix, non-uniform distribution of fibres, delamination at free edges, and the fibre-matrix composition itself) is likely to cause some wave spreading. Our intention is to assess the credibility of such homogenization in the case of stress wave propagation induced by impact and apply the experience gained to the non-stationary state of laminated composites together with the consideration of material damage.

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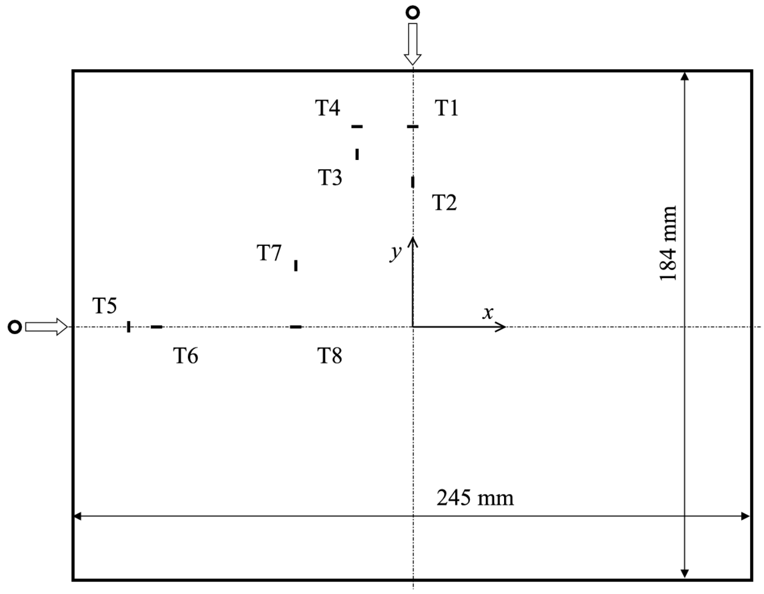

Figure 1: Geomtery of the panel, strain-gauges layout and the impact fashion.

Experiment

Investigated was the time response of a thin rectangular panel (w×h×t=245×184×2 mm) on the impact induced by a spheric projectile ($d = 4\,\mathrm{mm}$) moving at a velocity ranging between $30 \sim 50\,\mathrm{ms}^{-1}$. The projectile (or ball) was shot using an air-cannon so that it impacted one of the panel's narrow sides at a right angle – in the x-direction (along fibres) or in the y-direction (transverse to fibres, in the plane of the panel), see Figure 1.

There were eight strain-gauges (1 mm long) denoted as T1 – T8 placed on the front surface of the panel. The placement of the strain-gauges is shown also in Figure 1. The signal from the gauges was measured with the Tektronix TDS 2014 oscilloscope with the sampling frequency of 10 MHz. For each of the loading directions only the four strain-gauges were used (T1 – T4 for loading in y-direction and T5 – T8 for the x-direction. Approximately $100\,\mu$s long samples were collected during each measurement. The preparation and the experimental measurements were carried out by LENAM, s.r.o.

The panel was made up of Sigrafil fiber-reinforced unidirectional plies (fibres running in the x-direction) and the ball was made of glass. The material density of the panel and all the properties of glass were taken from references [8] and no verification could be done so far. The assumed mechanical properties of both materials are displayed in Table 1.

Computational model

We assume the material of the panels to be homogeneous from the macroscopic view and that the stress state in the panel can be regarded as plane stress due to relatively small

Table 1: Material properties and maximum phase velocity in Sigrafil ply and glass.

Material	E_1 [GPa]	E_2 [GPa]	ν_{12}	ρ [kg·m^{-3}]	$c_{\max}$ [m·s^{-1}]
Sigrafil	122.6	11.6	0.34	1500	9090
Glass	70.0	70.0	0.25	2500	5465

thickness of the panel. Therefore it is possible to write the equations of motion for the plane state stress in terms of displacements as

$$\begin{aligned}
C_{11}\frac{\partial^2 u}{\partial x^2} &+ C_{12}\frac{\partial^2 v}{\partial x \partial y} &+ C_{66}\left(\frac{\partial^2 v}{\partial x \partial y} + \frac{\partial^2 u}{\partial y^2}\right) &= \rho\frac{\partial^2 u}{\partial t^2}\,, \\
C_{12}\frac{\partial^2 u}{\partial x \partial y} &+ C_{22}\frac{\partial^2 v}{\partial y^2} &+ C_{66}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 u}{\partial x \partial y}\right) &= \rho\frac{\partial^2 v}{\partial t^2}\,,
\end{aligned} \tag{1}$$

where u and v are the x and y-displacements, respectively, C_{ij} $(i,j = 1,2,6)$ are the stiffness matrix components, t is time, and the axes x and y coincide with the principal material axes (axes of material symmetry) [4].

An important information needed for correct set-up of the computational model are the values of the phase velocities of waves travelling in the material. The material of the panel is highly orthotropic and so there is a significant difference in the values of the wave velocities for different directions, as opposed to isotropic material [4]. The maximum value of the phase velocity is that of a quasi-longitudinal wave travelling along the direction of fibres and it was calculated to be $c_{\mathrm{QL}} = 9090\,\mathrm{m{\cdot}s^{-}1}$. Glass is isotropic, hence the maximum velocity $c_{\mathrm{L}} = 4500\,\mathrm{m{\cdot}s^{-}1}$ holds for all directions. Taking this into account, the time step was set to $\Delta t = 0.05\,\mu$s.

The analysis was solved using contact FEA with central difference integration in the time domain. The finite element mesh of the panel consisted of square four-noded elements (edge length $a = 1\,$mm) with bilinear approximating functions. The mesh of the projectile consisted of 48 four-noded elements (see Figure 2). Both bodies were deformable. The MSC.Marc code was engaged in the analysis.

Prior to the contact analysis, a simplified analysis was performed, where the impact of the projectile was substituted with a time-dependent normal point load acting in the place of assumed contact. The loading was prescribed as a modified Gauss function in form

$$F(t) = \begin{cases} e^{-\xi^2}\,, \quad \xi = \tau(t - t_f)\,, & t \in \langle 0, 2t_f\rangle \\ 0\,, & t > t_f\,, \end{cases} \tag{2}$$

where $t_f = 12\cdot 10^{-6}\,$s controls the impulse duration and the parameter $\tau = \frac{1}{3}\cdot 10^6$ controls its frequency spectrum.

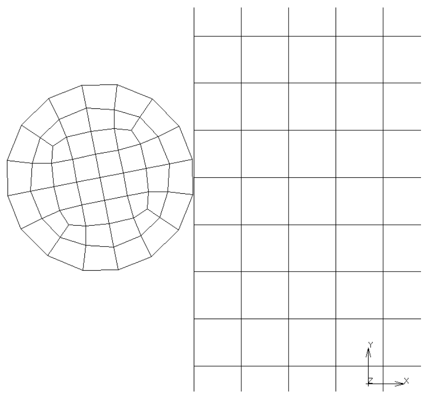

Figure 2: Detail of the FEA mesh used in contact analysis.

Results

For each loading type, the time response was measured subsequently several times. The speed of the projectile was first set to ensure good signal from the gauges. The chosen projectile speed, however, affected the surface of the panel in the contact region and the delamination occurred. This led to increasing differences in the signals between the subsequent measurements.

Micrographs of the panel's surface are displayed in Figure 6. The left image shows the structure of the material – fibres running vertically are visible. The right image shows the region on the front side of the panel close to the location of impact. The dark stripes denote areas of inter-fibre breakage and delamination after the transverse impact.

The experimental data obtained from the four strain-gauges for each of the two loading types were compared with the results of the FEA model. The measured signals were digitally filtered in order to compare only the frequency spectrum content that the numerical model was able to describe.

The two selected dependencies strain vs. time for the T6 and T8 strain-gauges are shown in Figures 3 and 4. In each of the graphs, there are three curves corresponding to the data from the first three measurements, one curve showing the numerical results from the contact analysis and one curve corresponding to the analysis with point-loading without contact (see legend for details).

It is obvious from these graphs that the numerical and experimental data show certain similar behavior. Since the numerical analysis assumed the state of plane stress, only the primary quasi-longitudinal (QL) and quasi-transverse (QT) waves and their reflections are present in the inside region of the panel. The calculated times of incoming QL and QT wave-fronts match well with those measured, except that the time shift increases with increasing measurement time. This is due to incorrect assessment of the material properties of the panel.

An important issue is that there occur significant differences between the measured and calculated signals outside the regions of the recognized QL and QT incoming wave-fronts, mainly in the transverse loading case. Prior to the contact analysis, it was believed that these differences would disappear when the contact is engaged. This consideration proved wrong.

The possible cause of such differences is that the process and conditions of the experimental measurement were not modelled correctly, i.e., that there some additional loading, such as multiple projectile impacts, different material properties causing longer contact duration, etc. This will be the concern of the following study. It is expected, however, that the main problem is the assumed material homogenization where all the reflections at the material interfaces are neglected.

An example of the signal travelling through the panel is displayed in Figure 5. The situation corresponds to time $20\,\mu$s when considering the contact between the panel and projectile. The left picture shows contours of strain in the x-direction when loaded along fibres while the right picture shows contours of strain in the y-direction when loaded perpendicular to fibres.

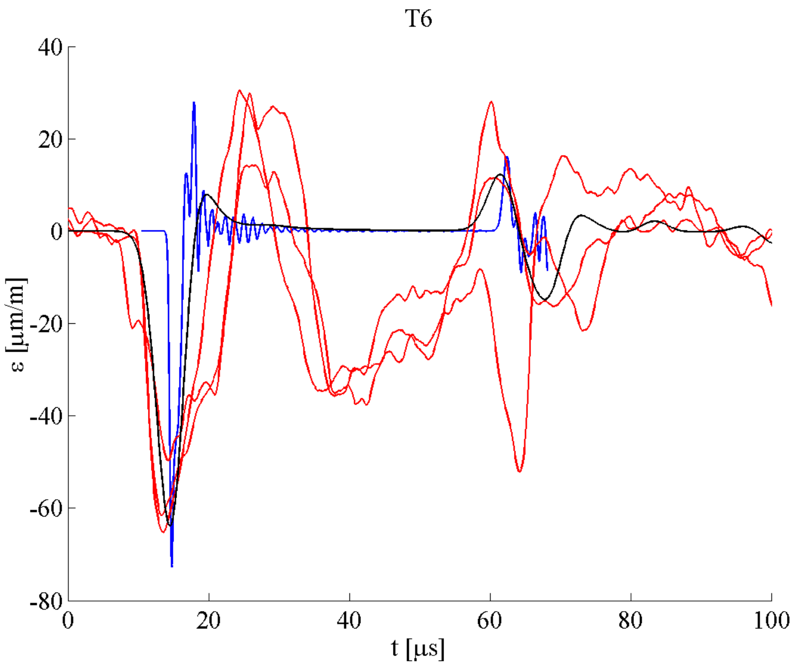

Figure 3: Measured and calculated time history of strain in T6 strain-gauge (red – measured, blue – contact FEA, black – point-load FEA).

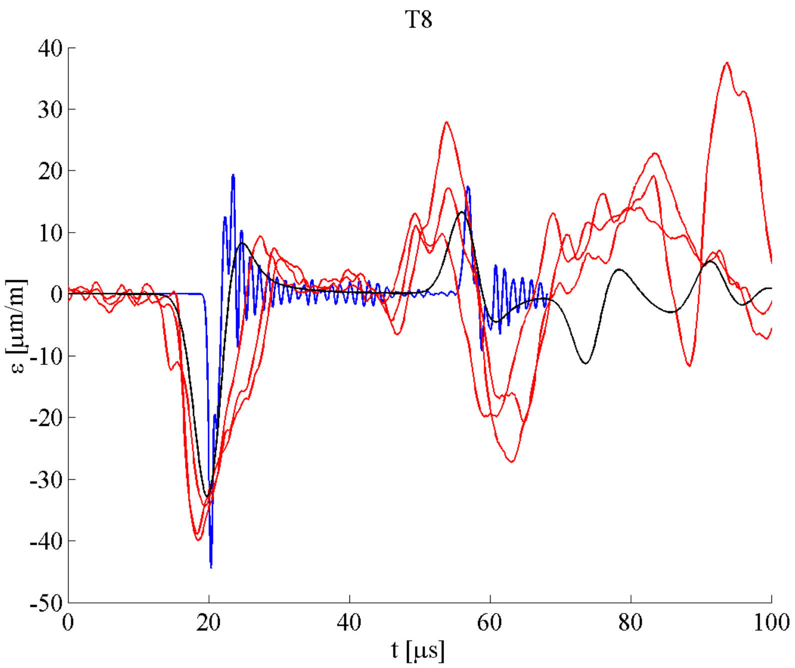

Figure 4: Measured and calculated time history of strain in T8 strain-gauge (red – measured, blue – contact FEA, black – point-load FEA).

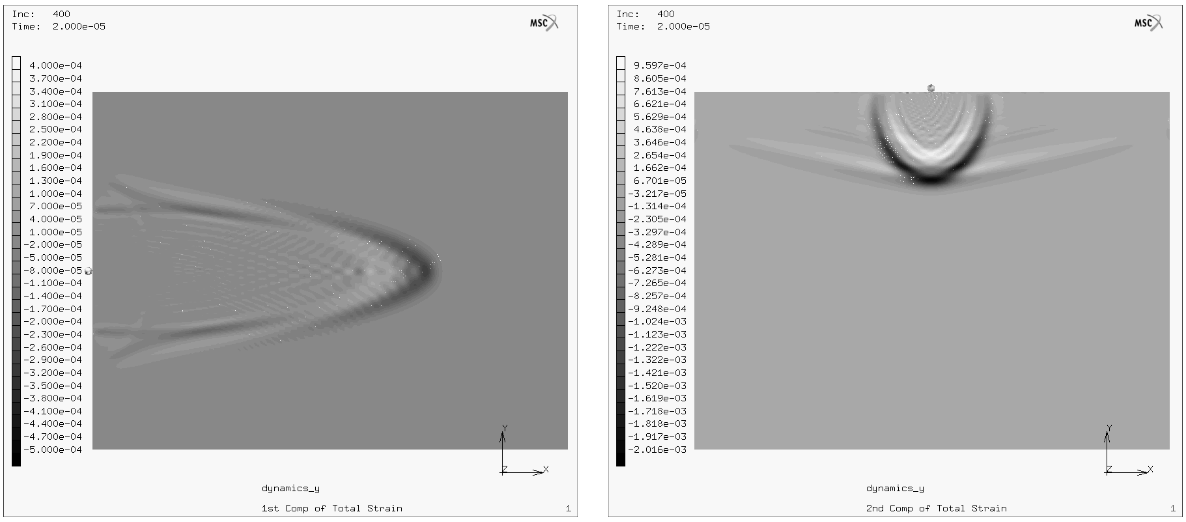

Figure 5: Contours of strain after the impact of projectile.

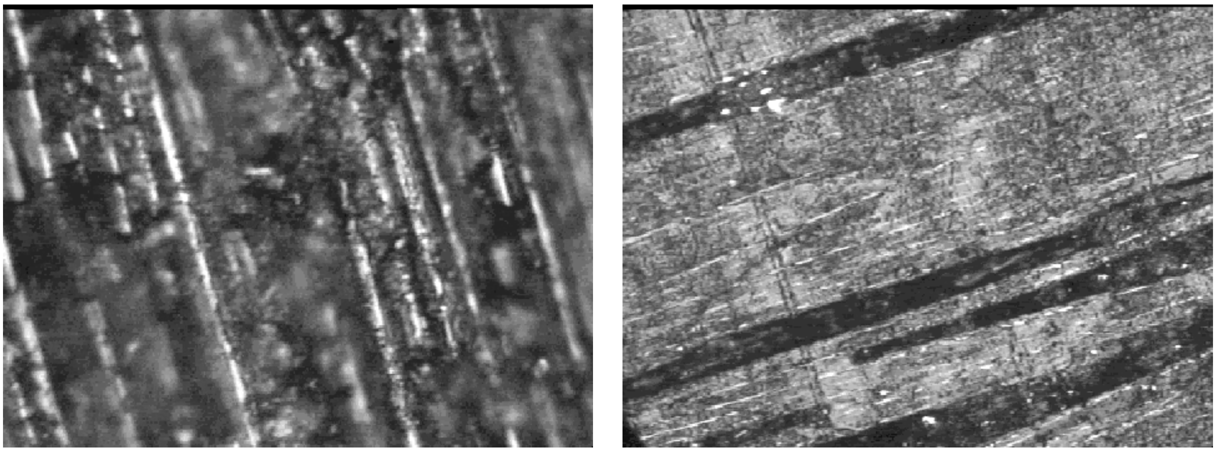

Figure 6: Micrographs of panel before (left) and after impact (right).

Conclusions

Experimental measurements of response of a thin orthotropic panel to impact loading induced by a projectile were carried out. The experimental measurements were believed to be non-destructive but the high impacting speed of the projectile caused some undesirable material damage, consequence of which was the decreasing quality of the signal collected from the strain-gauges.

Corresponding numerical simulations were performed and the results obtained were compared with the experimental data. In the case of both analyses – with point-loading or with contact of the two bodies – the results showed similar behaviour only for incoming QL and QT wave-fronts. Certain indispensable disturbances measured experimentally left unexplained. These are expected to be the consequence of the material non-homogeneity and remain the concern of further investigation.

In following study, our attention will be also focused on the fully three-dimensional analysis, in order to describe certain disturbances (such as of surface waves) that the plane state of stress, considered herein, is not capable to describe.

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