Loading of thin composite plate by low-speed impact

L Rychlíková¹, P Novák², J Skočilas³, M Žmindák², B Skočilasová¹ and J Soukup¹

¹ Faculty of Mechanical Engineering UJEP of Ústí n. L., 400 96 Ústí nad Labem, Czech Republic
² Faculty of Mechanical Engineering at the University of Zilina, 010 26 Žilina, Slovak Republic
³ Faculty of Mechanical Engineering CTU in Prague, 160 00 Praha, Czech Republic

E-mail: jan.skocilas@fs.cvut.cz

Abstract. The article summarizes the experimental results from the experiments of loading thin composite plates by low-speed impact. The plates are made on a 3D printer from the material onyx-glass fiber and onyx-carbon fiber. Another investigated material was a pre-impregnated (resin-kevlar) plate. The theory of the impact load of the plate and basic parameters of the tested plates are presented. The plates were repeatedly loaded with low-speed impact weights, the responses of the plate to the impact (wave propagation in the plate) were measured. The experiment is supplemented by a numerical analysis. Damage to the plates was evaluated by NTD methods.

1. Introduction

The solution of the problem of propagation of stress waves and deformations in plates has been investigated for a very long time. Rayleigh, Flügge, Timoshenko, Mindlin, and others contributed significantly to the solution. However, a satisfactory solution to this problem is not yet complete, especially for composite materials. The use of modern FEM methods finds out only satisfactory partial solutions. The shortcomings are mainly in determining the initial assumptions, both material and geometric. The article briefly outlines the theory of stress and strain wave propagation in thin plates. Particular attention is paid to composite plates, which contain both viscous and elastic components. At present, many authors are focused on the solution of shells. This is a very complex problem, especially with regard to the interaction of the pressure and tensile phases of the wave at the interface of material inhomogeneities. The smaller the particles, the greater the number of material interfaces that interact with each other at the front of the progressing wave, where greater attenuation and dispersion occur. The used material model has a significant effect on the solution (for composites, materials with diametrically different rheological properties are used, which give the structure higher strength). These material properties must be described for different speeds of a moving body, these are the modulus of elasticity, Poisson's ratio, thermal expansion of the material, etc. Composite materials are increasingly used in the design of machinery and equipment, machine parts, automotive and aerospace industry, medicine, and other fields. Plate and shell constructions made of these materials are one of the most widespread structural elements in modern technology, especially with regard to their excellent ratio of weight and stiffness (strength).

In this article, we deal with experimental and computational solutions of thin composite long-fiber plates, which are made by 3D printing (glass and carbon fibers, polyamide matrix reinforced with...
carbon fiber microparticles), as well as prepreg used in aviation. The plates were loaded with a low-
speed impact.

2. Solution
The stress and strain analysis of thin plates is performed by various methods. It is always based on an
analytical solution. This article presents the experimental solution, FEM and results from the solution
of NTD methods of plate damage (see below) [1].

2.1. Analytical solution
For the analytical solution of deformation and stress of a thin plate (generally bodies with known
geometry, material, load and connections to the environment) under impulsive (impact) loading, we
use the basic equations from the theory of elasticity [1, 2, 3]
- static equations (equilibrium of forces and moments which results in a reduction of the number
  of shear stress components from 9 to 6)
- geometric equations (equations expressing the relationship between the components of
deformation and displacement)
- physical equations (constitutive equations) expressing the relationship between stress and
strain. Constitutive equations allow us to describe the rheological properties of both isotropic
and orthotropic, elastic and viscoelastic or hereditary materials.

The solution arises from simplification with respect to
- geometry of the plate, i.e. the size and character of its deformation, support of the plate (plate
  free supported or embedded)
- type of excitation load (continuously constant or variable, impulse or time-dependent
duration)
- rheological properties of the plate material
- other simplifying assumptions depending on the used method of solution (small deformations,
  use of the principle of superposition, the effect of shear, linearity of relations, etc.).

![Figure 1. Thin plate model and punch load](image1)
Legend: F(t) – load force (time dependent) a, b, h – plate dimensions, c – radius of impact element, xF, yF – coordinates
of impact centre, (location of load force), σx, σy – bending stresses in axes x, y, τxy, τyx – torsional stresses, τxz, τyz –
shear stresses

![Figure 2. Deformation of plate element](image2)
Legend: A – general point, n - normal, n’ - normal under load, w, u, v – displacement in axis z, x, y, respectively, Z – displacement
from median surface, h – plate thickness

Figures 1 and 2 represent the scheme for calculating a thin plate. Various geometric models
(Kirchhoff’s, Rayleigh’s, Flügge’s, Timoshenko-Mindlin’s, which is closest to reality) and material
models (e.g. Hook’s, Voigt-Kelvin’s, Maxwell’s, and Zener's model of the standard body) are used for
the solution, which describes rheological properties of the investigated body. Here we present only
the basic relations for the Timoshenko-Mindlin geometric model (mTM), more detailed solutions for
different models are given e.g. in [1, 2, 3, 6, 7].

Plate displacements at particular axes
Displacements (1) are also function of surface rotation \( \varphi \) with respect to fig. 2. Rotation components are

\[
\varphi_x = \varphi_x(x, y, t) \quad \varphi_y = \varphi_y(x, y, t)
\]

where \( u, v, w \) – displacement in axis \( x, y, z \), \( \varphi_x, \varphi_y \) – rotation in axis \( x, y \).

We must realize that under the transverse impulse load of a rigid plate (thin plate), the plate oscillates - the so-called transient oscillation occurs. The solution of this oscillation depends on the rheological model of the plate, on whether the material is isotropic or orthotropic, elastic or viscoelastic. In the following text, only the solution of oscillations of a thin viscoelastic orthotropic plate at transverse impulse loading is described (this is a 2D problem, the solution of thick plates is a 3D problem).

The components of the plate deformation depending on the displacement components are then

\[
\varepsilon_x = \frac{\partial u}{\partial x} = -z \frac{\partial \varphi_y}{\partial x} = -z \frac{\partial^2 w}{\partial x^2}, \quad \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \Rightarrow \gamma_{xy} = -z \left( \frac{\partial \varphi_y}{\partial y} + \frac{\partial \varphi_x}{\partial x} \right) = -2z \frac{\partial^2 w}{\partial x \partial y}
\]

\[
\varepsilon_y = \frac{\partial v}{\partial y} = -z \frac{\partial \varphi_x}{\partial y} = -z \frac{\partial^2 w}{\partial y^2}, \quad \gamma_{xz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \Rightarrow \gamma_{xz} = \frac{\partial w}{\partial x} - \varphi_x = 0
\]

\[
\varepsilon_z = \frac{\partial w}{\partial z} = 0, \quad \gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \Rightarrow \gamma_{yz} = \frac{\partial w}{\partial y} - \varphi_y = 0.
\]

where \( \varepsilon_x, \varepsilon_y, \varepsilon_z \) - deformation of the plate in the direction of the axes under load. As follows from the previous, it is an impulse load, i.e. a dynamic process, i.e. we must consider the moment of inertia of the plate \( J \), when rotating in the individual axes,

\[
J \frac{\partial^2 \varphi_x}{\partial t^2} \neq 0 \quad J \frac{\partial^2 \varphi_y}{\partial t^2} \neq 0
\]

Motion equations for mTM [1] are

\[
\frac{\partial q_{xz}}{\partial x} + \frac{\partial q_{yz}}{\partial y} + p(x, y, t) = \rho h \frac{\partial^2 w}{\partial t^2}
\]

\[
q_{xz} \frac{\partial m_x}{\partial x} - \frac{\partial m_{xy}}{\partial y} = J \frac{\partial^2 \varphi_x}{\partial t^2}, \quad q_{yz} - \frac{\partial m_y}{\partial x} - \frac{\partial m_{xy}}{\partial x} = J \frac{\partial^2 \varphi_y}{\partial t^2}
\]

where \( J = \frac{h^3}{12} \rho \) - moment of inertia, \( q_{xz}, q_{yz} \) – shear forces, \( p \) – parameter (load), \( m_x, m_y \) – specific bending moments (in axes), \( m_{xy} \) – specific torque.

After substituting and arrangement, we get a system of three equations

\[
\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \frac{G_{xx}k + \varphi_x}{\rho} + \frac{\partial \varphi_x}{\partial x} G_{xx}k + \frac{\partial \varphi_y}{\partial y} G_{yy}k = - \frac{p(x, y, t)}{\rho h}
\]

\[
\frac{\partial^2 \varphi_x}{\partial t^2} + \frac{\partial^2 w}{\partial x^2} \frac{G_{xx}k + \varphi_x}{\rho h^2} + \frac{\partial \varphi_x}{\partial x} \frac{12 D_y}{\rho h^3} - \frac{\partial^2 \varphi_x}{\partial y^2} \frac{12 D_y}{\rho h^3} = \frac{\partial^2 \varphi_x}{\partial x \partial y} \frac{12 D_y}{\rho h^3} \left( D_y \mu_{xy} + D_{xy} \right) = 0
\]
where \( k \) - dimensionless coefficient respecting the trend of shear stress, \( D_x, D_y \) - modulus of stiffness in the axis \( x, y \), \( D_{xy} \) - torsional stiffness, \( \mu_{xy}, \mu_{yx} \) - elastic constants of orthotropic material. Then the required quantities for the displacement and rotation of the cross-sections are determined from the relations

\[
\begin{align*}
\varphi_y (x; y; t) &= \frac{4}{ab} F_o \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} p_{mn} \sin \alpha x \sin \beta y \cdot \sum_{j=1}^{3} A_j \int_{0}^{\frac{\pi}{\omega_j}} T_f (\tau) \sin \omega_j (t - \tau) d\tau, \\
\varphi_x (x; y; t) &= \frac{4}{ab} F_o \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} p_{mn} \cos \alpha x \sin \beta y \cdot \sum_{j=1}^{3} B_j \int_{0}^{\frac{\pi}{\omega_j}} T_f (\tau) \sin \omega_j (t - \tau) d\tau, \\
\varphi_{y}^{'} (x; y; t) &= \frac{4}{ab} F_o \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} p_{mn} \sin \alpha x \cos \beta y \cdot \sum_{j=1}^{3} C_j \int_{0}^{\frac{\pi}{\omega_j}} T_f (\tau) \sin \omega_j (t - \tau) d\tau
\end{align*}
\]

where \( A_i, B_i, C_i \) - coefficients, \( F_o \) - alone excitation force, \( T_f \) - dimensionless function of external load time, \( \alpha = \frac{n\pi}{a} \); \( \beta = \frac{m\pi}{b} \), \( m, n \) – elements of matrix, \( a, b \) – plate dimensions, \( \omega \) - frequency. A more detailed calculation is in the literature, e.g. [1].

Other quantities, i.e. components of displacements in the \( x, y \) axes, velocities in the individual axes and stresses for a specific mode of excitation load, can be found in the same way.

2.2. Numerical solution

The calculation was performed in the FEM ANSYS Workbench, ANSYS Mechanical, for 4 plates variants and for the impact from a height of 100, 150, 200, 250, 300, 350 and 400 mm above the plate. Both shell and volume models were used [5].

Shell models were, due to symmetry, solved as quarter or complete models. The complete shell model has been shown to be less prone to loss of convergence. However, its disadvantage is 4 times higher number of elements and the resulting long computational times. Models with fine mesh and coarse mesh were solved.

The quarter model with a coarse mesh had 934 linear shell elements with 1001 nodes. The impacting body (ball) was modeled as an ideally rigid body with 5442 elements and 1245 nodes. The full model has 6376 elements and 2246 nodes.

The fine mesh quarter model consists of 76176 linear shell elements and 76729 nodes. The total number of elements in the analysis was 82877 elements and 78217 nodes. The entire shell model with a fine mesh consists of 306916 linear shell elements with 308025 nodes. The full model with a fine mesh has 326726 elements and 312054 nodes (i.e. including the impacting body).

Volume models show a different character of the solution than models using shell elements. Above all, it is a slower onset of contact force and its flatter trend in time. These calculations were performed as a guide only.

2.3. Experiments

The experimental solution was divided into 3 parts, static, dynamic measurements and the use of non-destructive methods to identify damage to the composite plates. The test plates were made by 3D
printing from the material Onyx - glass fiber and from the material Onyx - carbon fiber, and also from prepreg (pre-impregnated carbon fiber). For the tests, 4 types of plates with fiber orientation listed in Table 1 were produced.

At the same time, test tapes for static tensile tests were produced, which served only for an indicative comparison of the strength of individual materials. The composition of the layers is shown in Fig. 3.

![Figure 3. Composition of the layers. 3D printing production.](image)

The orientation of the fibers in the individual layers of the individual samples is given in Table 1, where the dimensions of the test tapes for tensile tests are also given. The thickness of individual plates (and tapes) was 2 mm (for 3D printing, the thickness of carbon fibers was 0.125 mm, the thickness of glass fiber was 0.1 mm). For prepreg plates, the thickness of one prepreg layer is 0.25 mm, the fiber is impregnated with 40% epoxy resin, the plates were cured in an autoclave at a temperature of 125 °C and a pressure of 600 kPa.

Table 1 Specification for test samples of prepreg carbon fiber

| Layer number | Dimension [mm] | Angle of rotation of the fibers $\varphi$ [°] |
|--------------|----------------|---------------------------------------------|
|              | 120 x 120      | 250 x 25                                    |
| 1            | 0              | 0                                           |
| 2            | 0              | 45                                          |
| 3            | 90             | 0                                           |
| 4            | 90             | 0                                           |
| 5            | 90             | 0                                           |
| 6            | 90             | 0                                           |
| 7            | 0              | 45                                          |
| 8            | 0              | 45                                          |
For dynamic (impact) tests, a test stand was designed to enable the implementation of dynamic tests both at low speeds (up to 10 m.s\(^{-1}\)) and at high speeds (ballistic). The basic requirement for the stand is that it will not be excessively deformed or springed under load. The scheme of the stand for dynamic tests can be seen in Fig. 4 and 5.

**Figure 4.** Stand for dynamic tests - scheme  
Legend: 1 - washer, 2 - bolt, 3 - nut, 4 - washer, 5 - cylinder, 6 - solenoid, 7 - holder, 8 - sample frame, 9 - load cell sensor Kistler, 10 - frame

**Figure 5.** Sample frame  
Legend: 5 - bolt, 8 - sheet 1, 9 - square, 10 - upper dovetail, 11 - sheet 2, 12 - sample plate, 13 - link, 14 - ring, 15 - nave, 16 - plug, 17 - impact pin (removable), 18 - lower dovetail.

The stand is designed so that the impact body (or projectile) does not act directly on the measured plate, but through a plug (it is placed in the link - Fig. 5), which can set the position of impact on the plate (therefore there are holes in the cover plate to allow the impact off-center of the plate).

**Figure 6.** Assembled stand for ballistic tests  
**Figure 7.** View of the force sensor and holes for the impact of the plug
3. Results
The results are given for dynamic tests, tests of plate damage after impact by non-destructive method and for completeness also simulation results in Ansys.

3.1. Dynamics tests
The test plates were loaded with a low-speed impact and the contact force or its propagation through the plate in the transverse direction (in the direction of the z-axis) was determined. The low-speed impact was realized by the fall of the body onto the plug, which was placed in the link (Fig. 6). For this purpose, the stand (Fig. 6) was modified so that the nail gun for ballistic tests (high-speed) and its attachment was dismounted. A plexiglass tube with an inner diameter of 34 mm was installed on the stand, in which a test specimen weighing 394.7 g was moving. The measurement was performed repeatedly five times.

The weight fell on the plug from constant heights, the speed of impact of the weight was determined by calculation

| Height $h$ [mm] | 100 | 200 | 300 | 400 | 500 |
|----------------|-----|-----|-----|-----|-----|
| Impact speed $v$ [ms$^{-1}$] | 1,401 | 1,981 | 2,426 | 2,801 | 3,132 |

The measuring chain consisted of a KISTLER force transducer, an amplifier with a KISTLER 5015 measuring card, Charge meter, serial number 3055143. The timeline for determining the start of the recording was provided by a Tektronix 4 × 200 MHz oscilloscope.

Due to the large range of measurements performed, we will present only selected results. We deal with prepreg plates.

A plate that showed high stiffness values is a plate made of prepreg (prepreg carbon fibers) with a fiber orientation (0/0/90/90)s, for a drop height of 100 and 400 mm. This plate is compared with a similar plate with fiber orientation (0/0/0/0) s for the same fall heights.

![Figure 8](image_url)

**Figure 8.** Trend of force in the direction of the z-axis, drop height of the weight is 100 mm, impact on the center of the plate

Legend: Plate 120 × 120 mm, prepreg material, fiber orientation (0/0/90/90) s, x axis - time [s], y axis - contact force [N]

The value of the maximum force $F_{max}$ in individual measurements ranged from 45.3 N to 48.3 N, the average value was 47.0 N. The deviations of individual measurements from the average value of the maximum force reached a maximum of 3.62 %. Maximum of the force value was reached at about 0.0006 s after impact.
Minimum values of forces $F_{\text{min}}$ ranged from -11.2 N to -12.3 N, the average value reached -11.55 N. Deviations from the average value were less than 6.5 %, the minimum value was reached at 0.0015 s after the impact of the weight.

Deviations are caused by energy dissipation, especially friction losses when weights fall (almost impossible to eliminate), both losses in the material of the frame during the transmission of force to the sensor (cannot be determined) and in the test plate itself (it is a viscoelastic material).

**Figure 9.** Trend of force in the direction of the z-axis, drop height of the weight 400 mm, impact on the center of the plate

Legend: Plate 120 × 120 mm, prepreg material, fiber orientation (0/0/90/90) s, x axis - time [s], y axis - contact force [N]

The value of $F_{\text{max}}$ in individual measurements ranged from 94.4 N to 99.2 N. The average value was 96.6 N. Deviations from the average value were less than 2.7 %. Maximum of the force value was reached in 0.00032 s.

$F_{\text{min}}$ values ranged from -17.0 N to -21.9 N, the average value was -18.73 N, deviations from the average value in one case reached almost 17 % (16.96 %), in other cases up to 10 %, minimum of the force values were reached at 0.00136 s.

**Figure 10.** Trend of force in the direction of the z-axis, drop height of the weight 100 mm, impact on the center of the plate

Legend: Plate 120 × 120 mm, prepreg material, fiber orientation (0/0/0/0) s, x axis - time [s], y axis - contact force [N]
For a prepreg plate with fiber orientation (0/0/0/0) s, the following results were obtained for heights of 100 and 400 mm.

This plate has a different arrangement of reinforcement than the plate in the previous case, but it is made of the same material. The value of the maximum force $F_{\text{max}}$ in individual measurements ranged from 56.8 N to 61.4 N, the average value was 59.48 N. Deviations from the average value reached a maximum of 7.76%. Maximum of the force value was reached in about 0.0002 s.

Minimum values of forces $F_{\text{min}}$ ranged from -16.2 N to -19.7 N, the average value reached the value of -17.95 N. Deviations from the average value were max. 9.75%. Deviations are caused by energy dissipation (friction losses, losses in the material, frame and the plate itself). The minimum value of force was reached in the time 0.00096 s.

![Figure 11](image)

**Figure 11.** Trend of force in the direction of the z-axis, drop height of the weight 400 mm, impact on the center of the plate

Legend: Plate 120 × 120 mm, prepreg material, fiber orientation (0/0/0/0) s, x axis - time [s], y axis - contact force [N]

Fig. 11 is a graph showing the trend of the force when a weight falls from a height of 400 mm. $F_{\text{max}}$ in individual measurements ranged from 114.4 N to 125.3 N. The average value was 120.35 N. Deviations from the average value were less than 5% in all cases. Maximum of the force value was reached in 0.00016 s.

$F_{\text{min}}$ values ranged from -25.0 N to -28.2 N, the average value was -26.78 N, deviations from the average value reached a maximum of 6.63% (25.0 N), on average only 3.77. Minimum of the force value was reached in 0.0008 s.

From the measured values it can be deduced that the plate with fiber orientation (0/0/0/0) s is stiffer than the plate with orientation (0/0/90/90) s. This follows both from the times when the maximum (minimum) values of forces were reached and from the magnitude of these forces.

3.2. Non-destructive experiments

During the low-speed impact tests, the composite plates were damaged visibly on the surface. It was obvious that damage could also occur inside the plate before the damage appeared on the surface. Therefore, the examination of the damage of the plate made of composite viscoelastic material was performed using the non-destructive method (IR NDT).

A plate of prepreg carbon fibers with an arrangement (90/0/45/0) s was selected for this test. This plate was stressed during the test by repeated low-speed impacts from a height of 700 mm, 800 mm and 1000 mm. In the punch, a hemispherical tip was replaced with a sharp tip (0.5 mm tip radius). The first damage began to show after the second impact from a height of 700 mm (crack nucleus). Then the
height was increased to 800 mm (2 impacts), the crack gradually lengthened and widened, then 2 impacts were made from a height of 1000 mm. Subsequently, the test was interrupted and the plate removed from the stand. The length of the crack on the face side reached 29.3 mm, on the reverse side there was a bulge about 14.3 mm wide and about 30 mm long, the bulge is symmetrically distributed along the axis (the axis is given by the crack on the face side) - Fig. 12 and Fig. 13.

![Figure 12](image1.png) ![Figure 13](image2.png)

**Figure 12.** The face of the damaged plate shows a crack in the surface layer  
**Figure 13.** The reverse side of the damaged plate shows a convexity of the surface layer

Damage to the plate after the impact test was detected by two methods, which differed in the excitation of the examined object. Both methods are based on the detection of energy emitted after excitation of an object into the environment - therefore we speak about non-destructive testing (NDT). We detect inhomogeneities in the structure of the object, so it is necessary to choose a suitable method of excitation and response detection. Inhomogeneities in this case are cracks, defects, gaps and holes in the composite object. These inhomogeneities in the composite material can be caused, for example, by the impact of a projectile, excessive compression of the object, or other, artificial creation of a defect (see our case). In our case, we limited the detection of radiated energy in the range of medium waves 500 (MWIR) using a cooled thermal detectable infrared camera FLIR SC7500 with a frame rate of 383 Hz and a resolution of 320 × 256 pixels.

In the first case, the EDEVIS ultrasonic system in the frequency range of 15 kHz to 25 kHz was used to excite the object, the signal was modulated by the low-frequency component fLOCKIN. The maximum power of the system is 2.2 kW. The arrangement of the measurements is evident from Fig. 14, including the mounted measured object in the sonotrodes.

In the second case (on the same sample), the OTvis optical system was used for excitation. Two halogen reflector lamps were used to excite the sample, which are switched on and off alternately with the required power (it is adjustable). The maximum power of the lamps is 2 × 2.5 kW. The process period (off - on) is controlled by the frequency component fLOCKING. Bandpass filters in the MWIR medium wavelength range are used. In our case, we used several activation frequencies (frequencies of lighting on and off) - repeated measurements to detect damage.

Note the different attachment of the sample (vertical) and the thermal camera - perpendicular to the plate - Fig. 15.
In the thermogram in Fig. 16 there are images from the thermal camera of the undamaged plate in the upper part (no damage of the plate is detected, it would show a symmetrical pattern in complex and phase display - the sample is symmetrical), in columns b) and c) there are images of damaged plate, a significant anomaly in the center of the figure occurs (apparent extent of damage).

![Undamaged plate thermogram](image)

![Damaged plate thermogram](image)

**Figure 14.** Arrangement of IR NTD workplace with ultrasound excitation (UTvis method)

**Figure 15.** Optical excitation of a damaged sample

**Figure 16.** Thermogram of undamaged and damaged plates, excitation by UTvis, from the impact side

Legend: a) thermogram (Temperature), b) complex image (Complex), c) phase image (Phase)

Fig. 17 shows the results of OTvis damage measurements. The method allows the detection of the response to radiation with a sensitivity 100 × to 1000 × greater than the best thermal camera can. This
method also avoids problems with determining the emissivity of the object, but it is not suitable for testing thermosensitive objects (samples) when applying a long excitation time (heating the sample).

![Image](95x550 to 262x703)

**Figure 17.** OTvis excitation method. Phase display, 3 Hz frequency activation on the left, 2 Hz on the right

The presented measurements proved the possibility of detecting damage to the examined objects by means of ultrasonic or optical NDT (Non destruction testing) method, especially in thin or shell materials. The possibility of using this method is also important in the case that the impact occurs on the side of the examined object that is inaccessible to us.

Composites damage is commonly used to describe poor adhesion, matrix separation from the matrix, delamination, fiber breakage, and their combinations. The above method of detecting composite damage can help shed light on this issue. We emphasize that in our case the inhomogeneity was found to be a crack that came to the surface of the analyzed sample.

### 3.3. Simulation

The experimental solution of forces at low-speed loading of a thin composite plate was supplemented by a simulation calculation. The calculation of forces was performed in the ANSYS Mechanical program. The plate is loaded by a transverse impact. The calculation was preceded by an indicative experimental solution (see section 5), which gave us an idea of the trends of these forces and allowed us to set the basic conditions of the calculation. The plate is firmly embedded around the perimeter. Since this is a symmetrical plate (square), we can use a quarter model.

The procedure in the ANSYS Workbench programming environment involved these steps:
- generation of a mesh for individual models (4 variants of plates were used) and 2 simulation models - shell (these models were realized as quarters with a fine and coarse network) and a volume model - always for all plate variants
- mesh reload to ANSYS Mechanical
- loading the basic mechanical properties of each model.

The individual plates were made of unidirectional carbon fibers, the arrangement of the fibers is as follows:

- variant A = (0/0/90/90/90/90/0/0)
- variant B = (0/0/0/0/0/0/0/0)
- variant C = (45/45/45/45/45/45/45/45)
- variant D = (90/0/0/0/0/0/0/90).

The dimensions of the plates are 120 × 120 × 2 mm, of which the 10 mm of the plate is firmly embedded around the perimeter.
The loading of the plate is a low-speed impact of a body weighing 394.7 g from a height of 100 mm, 150 mm, 200 mm, 250 mm, 300 mm, 350 mm and 400 mm. The material properties were chosen pre-defined from material table, listed in ANSYS.

As mentioned above, the calculations (simulations) were performed on shell and volume models. Due to the symmetry of the plate, the shell models were solved as 1/4 models, or complete. Calculations have shown that the complete shell model is less prone to loss of solution convergence than the 1/4 model - a high value of "hourglass" energy is produced. The big disadvantage of the full shell models is 4 times a larger number of elements and the resulting long computational times.

Fig. 18 shows the results of all analyzes for the fiber arrangement in plate A (0/0/90/90) s. The results show that the quarter model with a coarse shell network and the full model with a fine shell network show the highest stiffness at the moment after the impact - the contact force increases the fastest. On the contrary, volume models at this moment show the lowest stiffness.

![Figure 18. The trend of the contact force for the plate in variant A, all heights and meshes](image)

Fig. 19 is a comparison of the simulation results for the variant of the arrangement of fibers A, B and D at the impact from a height of 100 mm on the plate. The results of the quarter shell model with fine mesh and the full shell model with fine mesh are compared. The results show that the plate according to variant B in a time around $1 \times 10^{-4}$ s there is a sharp change in contact force and from this time the results of the quarter and the full model begin to differ. The quarter model shows faster oscillations of the solution. For the remaining plates (A, D) there is a good agreement for both models.
Figure 19. Comparison of the trend of the contact force for the full and 1/4 shell model of plates A, B, D and the impact from the height h = 100 mm

Fig. 19 is a comparison of the simulation results for the variant of the arrangement of fibers A, B and D at the impact from a height of 100 mm on the plate. The results of the quarter shell model with fine mesh and the full shell model with fine mesh are compared. The results show that the plate according to variant B in a time around $1 \times 10^{-4}$ s there is a sharp change in contact force and from this time the results of the quarter and the full model begin to differ. The quarter model shows faster oscillations of the solution. For the remaining plates (A, D) there is a good agreement for both models.

Figure 20. Comparison of the trends of the contact force for the full shell model and the half-volume model of the plates A, B, D and the impact from the height h = 400 mm
We verified this interesting behavior of the trend of the contact force in the variant of the arrangement of fibers B (0/0/0/0) s on the modified variant B, which we called IMPREF. Compared to the original variant B, variant B IMPREF has a modified arrangement of fibers, namely (1/-1/0/0/0/-1/1). With this calculation, we wanted to verify whether a rapid decrease in contact force is maintained after reaching the first maximum. In Fig. 21 it can be seen that the waveforms for variant B (BJC line in Fig.) and IMPREF variant B (BJCI line in Fig.) are very similar and in the critical area (i.e. in the area of the first large change of contact force) practically identical. Variant B IMPREF started to diverge later than variant B. From this it can be concluded that this is physically real behavior.

![Graph](image)

**Figure 21.** Comparison of the trend of the contact force for variant B and B IMPRF, impact height \( h = 400 \text{ mm} \)

### 4. Conclusion

The article briefly presents the results of the experimental solution of stress or force wave propagation in thin composite plates with viscoelastic material, which is part of a long-term research of solutions of dynamically loaded thin plates by transverse impact. It builds on the work previously done mainly in the field of analytical solutions and was focused on the experimental solution of composite plates made of prepreg carbon fibers and 3D printing on a MarkForget Two printer. The plates were loaded with a low-speed impact (drop of the test specimen) on a punch by which the forces were transmitted to the test plate. Regarding the experimental solution (force measurement), it is necessary to state that when measuring the impact or reaction force, the measuring apparatus did not record (measure) the static component of the force, only the dynamic component. The sampling frequency was 100 kHz, the results were in the order of tens of N. To more accurately capture the onset of forces, it would be necessary to use the sampling frequency in the order of MHz.

During the tests, the structure of the plate was damaged after repeated impacts. To assess this damage, a method of non-destructive testing of defects in thin plates using a thermal imager was designed, implemented and tested. The plate was excited both by ultrasound (UTvis method) and optically (halogen lamp flashes - OT vis).

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