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# Determination of value of shear modulus for linear stress-strain relationship in case of impact on composite plate

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**Abstract:** This work is focused on numerical investigation of the behavior of composite plate under low-velocity impact loading. Using linear stress-strain relation the value of shear modulus was determined via optimization method based on the comparison of deflection curves between performed experiments and numerical simulations for various impact velocities. Linear dependence of shear modulus on impact velocity was observed.

**Keywords:** UD composite, Low-velocity impact, Drop tester

## 1. Introduction

The composite materials are used in wide range of applications such as aerospace or automotive industry where they have become the preferable alternative to conventional materials. These materials are popular because of their high stiffness to weight ratio, corrosion resistance and mainly "custom" product design variability. The main disadvantage of the composite materials is the predisposition to fragile failure and damage that is irreversible and causes stiffness and strength reduction of composite structures [5, 6]. The basic material properties, such as Young's moduli, Poisson's ratios and strengths are usually obtained from tensile or bending static tests. Comparison of experiments and numerical analyses using linear stress-strain relationship indicates that properties of material model of composite should be partially adjusted in order to achieve agreement. The dynamical stiffening which change the behavior of composite materials under dynamical loading is necessary to consider in composite applications to ensure the safety in case of all expected loads. It is also important to consider the random impact loads which can cause the damage too, for example dropping the tool during maintenance.

This paper is focused on investigation of the behavior of composite plate under low-velocity impact loading. The change of parameters of material model on impact velocity of impactor was investigated by comparison of time-deflection curves from performed experiments and from numerical simulations.

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## 2. Experiment

The used material was undirectional fiber-reinforced composite made of 4 layers of prepreg designated as 4EHKF420-UD24K-40 consisting of Toray T600SC fibers and epoxy resin. The material properties of this composite were determined from quasi-static tensile and bending tests using correlation of experimental results and results of numerical simulation in [1]. The resulting material properties are summarized in Table 1 [1].

**Table 1. Elastic material parameters of composite material determined by static tests.**

| $E_1$ [GPa] | $E_2$ [GPa] | $G_{12}$ [GPa] | $\nu_{12}$ [-] | $\rho$ [kg·m$^{-3}$] |
|---|---|---|---|---|
| 153.4 | 7.8 | 4.5 | 0.28 | 1510 |

A series of impact tests was performed on rectangular plates with dimensions 135 × 270 mm and thicknesses 1.15 mm. The fibers directions of undirectional composite was parallel to the longer side. The plates were simply supported along the shorter edges on the steel stand with the overlap 10 mm at each side (see Fig. 1).

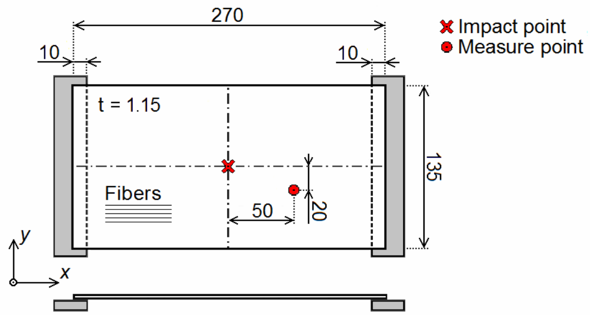


**Fig. 1.** Geometry of composite plate and the position of measure apparatus.

Drop weight testing machine was used to induce impact on the composite plates. The impactor of testing device was accelerated only by gravity. It consisted of a force sensor (Brüel&Kjær 8200) with steel spherical head with radius 15 mm, slider and aluminium frame. The total mass of impactor was 217 g. The response of the composite plates was measured during the impact event by laser sensor (OptoNCDT 2200) in selected off-axis point. The impact location was always in the middle of the plate. The impact velocity $v$ varied between 0.5 m·s$^{-1}$ and 3 m·s$^{-1}$, the step was 0.5 m·s$^{-1}$. Three plates were tested for each impact velocity.

## 3. Numerical model

Numerical simulations were performed using finite element analysis (FEA) in LS-Dyna. Explicit solver based on central difference scheme for time integration was chosen for simulation (calculated stable time step $\Delta t = 0.275$ µs). The simulations were performed up to time 25 ms after initial contact of impactor and plate. The large strain theory was assumed. The analysis was considered as fully contact problem of four elastic deformable bodies. The plate was meshed using shell elements with four layers, the impactor and the two supports using solid elements. The complex shape of the impactor was simplified and only the head of impactor was modelled with added mass to reach its total weight. The behaviour of the composite plate was described using transversely isotropic material model [2, 3] (in LS-Dyna MAT_54).

## 4. Optimization process

An optimization process handled using OptiSLang 3.2.0 was performed in order to minimize the objective function (residuum $e$) defined as

$$e = \sum_{i=1}^{n} \left( w_i^E - w_i^S \right)^2 , \tag{1}$$

where $w_i^E$ and $w_i^S$ are the deflections of plate from experiment and numerical simulation respectively and $n$ is number of time steps - in this study $n = 100$.

At first the sensitivity analysis was performed in order to determine the quadratic correlation coefficients between elastic moduli $E_1$, $E_2$ and $G_{12}$ and residuum $e$ (see Tab. 2). For the investigated range of impact velocities shear modulus $G_{12}$ was chosen as the parameter with the most significant influence on residuum $e$. Optimization was performed for each impact velocity in order to determine $G_{12}$ using nature based simple design improvement algorithm [4].

**Table 2. Quadratic correlation matrix**

| $v$ [m·s$^{-1}$] | $E_1$ [GPa] | $E_2$ [GPa] | $G_{12}$ [GPa] |
|---|---|---|---|
| 0.5 | 0.498 | 0.127 | 0.245 |
| 1.0 | 0.579 | 0.069 | 0.406 |
| 1.5 | 0.166 | 0.076 | 0.434 |
| 2.0 | 0.316 | 0.058 | 0.443 |
| 2.5 | 0.257 | 0.123 | 0.664 |
| 3.0 | 0.259 | 0.305 | 0.771 |

## 5. Results

In Table 3 are listed the magnitudes of residual $e_{\mathrm{OPT}}$ for optimized value $G_{12}$ and $e_{\mathrm{ORIG}}$ for original value obtained from tensile tests mentioned in Table 1.

Fig. 2 compares the identified dependence of material parameter $G_{12}$ on impact velocity with the approximation of obtained results via linear polynomial function. Values for an impact velocity 0 m·s$^{-1}$ are the static value of $G_{12}$.

**Table 3. The dependence of residuum on impact velocity**

| $v$ [m·s$^{-1}$] | 0.0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|
| $e_{OPT}$ | – | 1.76 | 6.20 | 6.69 | 8.34 | 20.29 | 50.83 |
| $e_{ORIG}$ | – | 3.46 | 21.08 | 102.10 | 207.45 | 776.98 | 2221.94 |

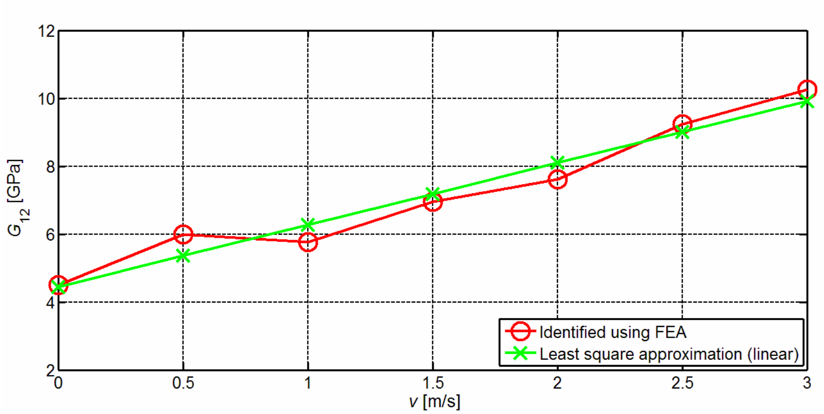


**Fig. 2.** The identified dependence of material parameter $G_{12}$ on impact velocity.

Fig. 3 shows the comparison of deflections obtained from experiments and from numerical simulations for all considered impact velocities. Two time-deflection dependencies are shown in case of numerical simulation for every impact velocity – the dependence of optimized and of original (static) material parameter $G_{12}$.

The calculated contact force for optimized material parameter $G_{12}$ is compared with experimental data from force sensor for impact velocity 1 m·s$^{-1}$ and 2.5 m·s$^{-1}$ in Fig. 4 and 5.

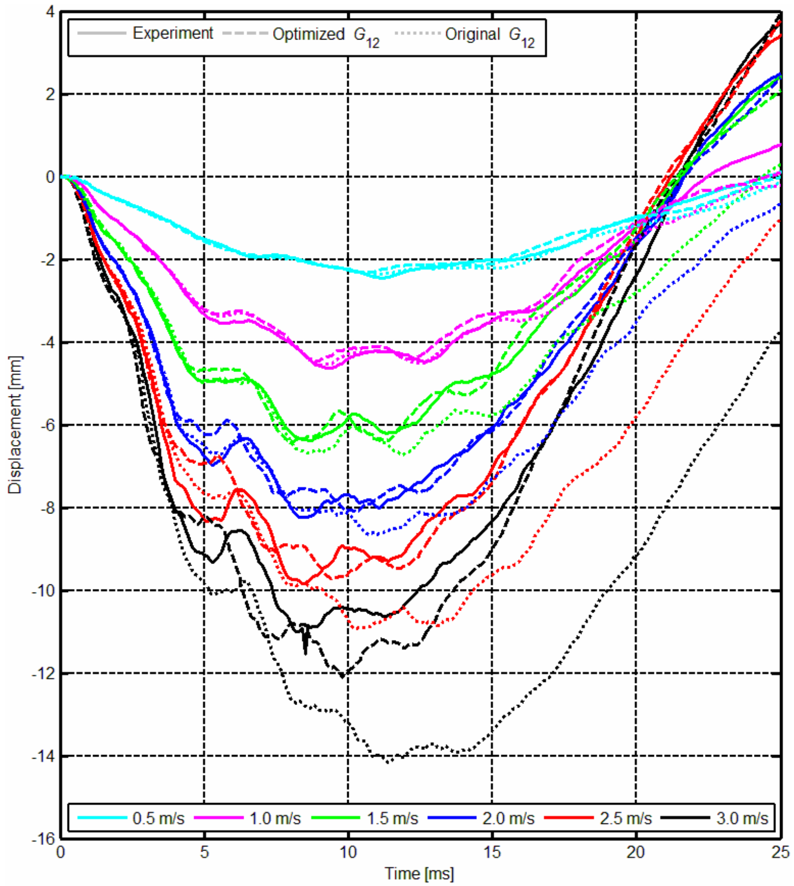


**Fig. 3.** Time-deflection comparison between experiment and numerical simulation for all impact velocities (solid – experiment, dashed – identified $G_{12}$, dotted – original $G_{12}$).

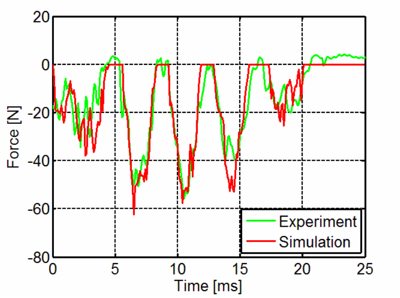


**Fig. 4.** Contact force comparison for impact velocity 1 m·s$^{-1}$.

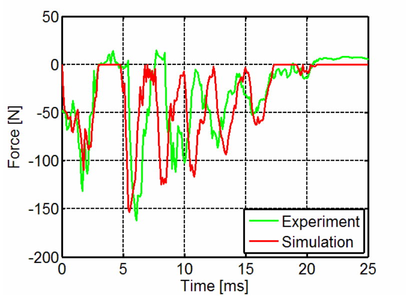


**Fig. 5.** Contact force comparison for impact velocity 2.5 m·s$^{-1}$.

## 6. Conclusion

Experiments of impact on composite plates with various impact velocities were performed. Initially, material constants obtained from static tensile tests were used for numerical analyses. Difference between experimental and numerical results was increasing with increasing of impact velocity of the impactor.

The study of the influence of each elasticity constant was performed. The objective function (residuum), which describe difference between experimentally and numerically obtained time dependence of deflection of the plate, was defined. The quadratic correlation coefficients were enumerated in order to determine which material constant has the largest influence on the residuum. It was observed, that shear modulus $G_{12}$ has the largest influence on the residuum in the whole range of investigated impact velocities.

Optimization was performed for each impact velocity in order to determine $G_{12}$. Almost linear dependence of $G_{12}$ on impact velocity was found.

The fact, that the most important parameter is $G_{12}$ is probably caused by position of the measurement point. Experiments with measurement points in different locations will be performed in the future in order to determine the corresponding dependence of two other moduli and possibly Poisson's ratio.

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