EAN 2017
55th conference on experimental stress analysis

Identification of impact force on composite textile plate for impacts with various energies

Jan Bartošek[1, a], Vladislav Laš[1], Tomáš Mandys[1] and Robert Zemčík[1]

[1] NTIS – New Technologies for Information Society, Faculty of Applied Sciences, University of West Bohemia, Univerzitní 8, 306 14, Plzeň, Czech Republic

[a]bartose4@ntis.zcu.cz

Keywords: impact force identification, inverse problem, drop weight test, composite material, delamination, damage, structural health monitoring

Abstract. Identification of impact force from measured response of composite plate is performed in this paper for various impact energies. Method based on transfer functions in time domain is used. Identification was performed on glass-epoxy textile laminated plate, which was simply supported and impacted by drop weight with various impact velocities up to occurrence of significant damage of the plate. Identification results and possibility to identify impact force on damage structure is discussed.

Introduction

Identification of impact force is problem of estimation of unknown force from signals measured by sensors placed on construction. Different quantities, which are not directly related to impact force, can be measured by sensors. Mostly piezoelectric sensors or accelerometers are used to measure strains or acceleration of construction. This approach is also called indirect measurement and can be used as a part of structural health monitoring (SHM) system of composite structure. Low-velocity impact events on composite structure can induce delamination of individual plies which can be inside of the material and hidden for classical visual inspections. SHM can replace time and cost expensive methods that would be needed for finding of such damage in construction.

Several methods were used to identify impact forces but mostly in laboratory conditions and for limited amount of loading [5]. Additionally, impact force is often identified virtually by simulated experiment, when numerical model needs to be calibrated [3] and more complex problems like sensor distribution can be solved [4]. Nearly industrial problem of identification of impact force on pressure vessel was solved by Atobe et al. [1].

Identification method

The identification method used in the paper is based on the deconvolution of signals in time domain. The assumptions are validity of principle of superposition, impact loading limited to one place and measurement in K discrete time steps. Then the response of sensor s can be expressed in matrix form

$$\mathbf{u}^s = \mathbf{G}^s \cdot \mathbf{f}\,, \tag{1}$$

where $\mathbf{u}^s = \left[u_1, u_{2,} \ldots, u_K\right]^T$ is vector of response, $\mathbf{f} = \left[f_1, f_{2,} \ldots, f_K\right]^T$ is vector of applied forces and $\mathbf{G}^s$ is matrix composed of time shifted impus resoponse vetctors of sensor s.

This matrix must be determined before the identification process. The impulse response vectros can be estimated directly from numerical model or indirectly from measurement by

$$\mathbf{F}\cdot\mathbf{g}^s = \mathbf{u}^s\,, \tag{2}$$

where $\mathbf{F}$ is matrix simlarly composed as matrix $\mathbf{G}^s$ but from vectors of impact forces, $\mathbf{u}^s$ is vector of coresponding responses and $\mathbf{g}^s$ is unknown impuse response. The Eq. (2) can be rewriten for *N* measuremetns in form

$$\begin{bmatrix}\mathbf{F}_1^s\\ \mathbf{F}_2^s\\ \vdots\\ \mathbf{F}_N^s\end{bmatrix}\cdot\mathbf{g}^s = \begin{bmatrix}\mathbf{u}_1^s\\ \mathbf{u}_2^s\\ \vdots\\ \mathbf{u}_N^s\end{bmatrix}. \tag{3}$$

This equation was solved in the paper by the least square method and estimation of impulse response $\hat{\mathbf{g}}^s$ was obtained.

The impact force history estimation $\hat{\mathbf{f}}$ is set as a solution of Eq. (1). For the measurement using *S* sensors the equation can be rewritten in form

$$\begin{bmatrix}\mathbf{G}^1\\ \mathbf{G}^2\\ \vdots\\ \mathbf{G}^S\end{bmatrix}\cdot\mathbf{f} = \begin{bmatrix}\mathbf{u}^1\\ \mathbf{u}^2\\ \vdots\\ \mathbf{u}^S\end{bmatrix}, \tag{4}$$

which was solved in the paper by Tikhonov regularization method with the non-negative constraint representing positive values of contact forces [2].

The correctness of the inverse solution can be characterized by Euclidean norm of residuum vector which is comparison of measured and calculated response

$$r = \left\|\mathbf{u}-\hat{\mathbf{u}}\right\|. \tag{5}$$

Response $\hat{\mathbf{u}}$ calculated from the inverse solution can be expressed from Eq. (1) for estimated impulse responses

$$\hat{\mathbf{u}}^s = \mathbf{G}^s\cdot\hat{\mathbf{f}}\,, \tag{6}$$

or from Eq. (2) for estimated impact forces

$$\hat{\mathbf{u}}^s = \mathbf{F}\cdot\hat{\mathbf{g}}^s. \tag{7}$$

Impact force identification error was defined as weighted comparison of identified and measured impact force

$$e_{\mathbf{f}} = \frac{\sqrt{\frac{1}{I}\sum_{i=1}^{I}\left(f_i-\hat{f}_i\right)^2}}{\max(\mathbf{f})}\times 100\ [\%]\,,\quad \forall i: f_i > \frac{\max(\mathbf{f})}{2}\ \vee\ \hat{f}_i > \frac{\max(\mathbf{f})}{2}\ , \tag{8}$$

where I is total number of compared elements. The constraint for choice of individual elements for comparison was considered to suppress errors from small forces which have low importance.

Experiment

The impacts on composite plate were performed experimentally on the impact device which consists of impactor with total mass of 2.336 kg and aluminum support frame. Hemispherical tip of the impactor with radius of 15 mm was equipped with force sensor *Kistler 9712B5000*. The impacts were performed on square composite plate made from three layers of glass fabric with plain weave (816 g/m^2) and epoxy resin *Epicote MGS LR 385*. The plate was simply supported around its perimeter by steel support and it was impacted in the center. Displacements of the plate were measured by three laser contactless displacement sensors (two pcs. of *OptoNCDT 2300-50* and one pc. of *OptoNCDT 2200-50*). Data acquisition of signals from lasers and force sensor were performed by *NI cDAQ-9178*, with modules NI 9215 and NI 9234, with sampling frequency of 10 kHz. Total length of recorded data was 50 ms which corresponds to 500 samples. The experimental setup is shown in *Fig. 1* and the important dimensions are in *Table 1*.

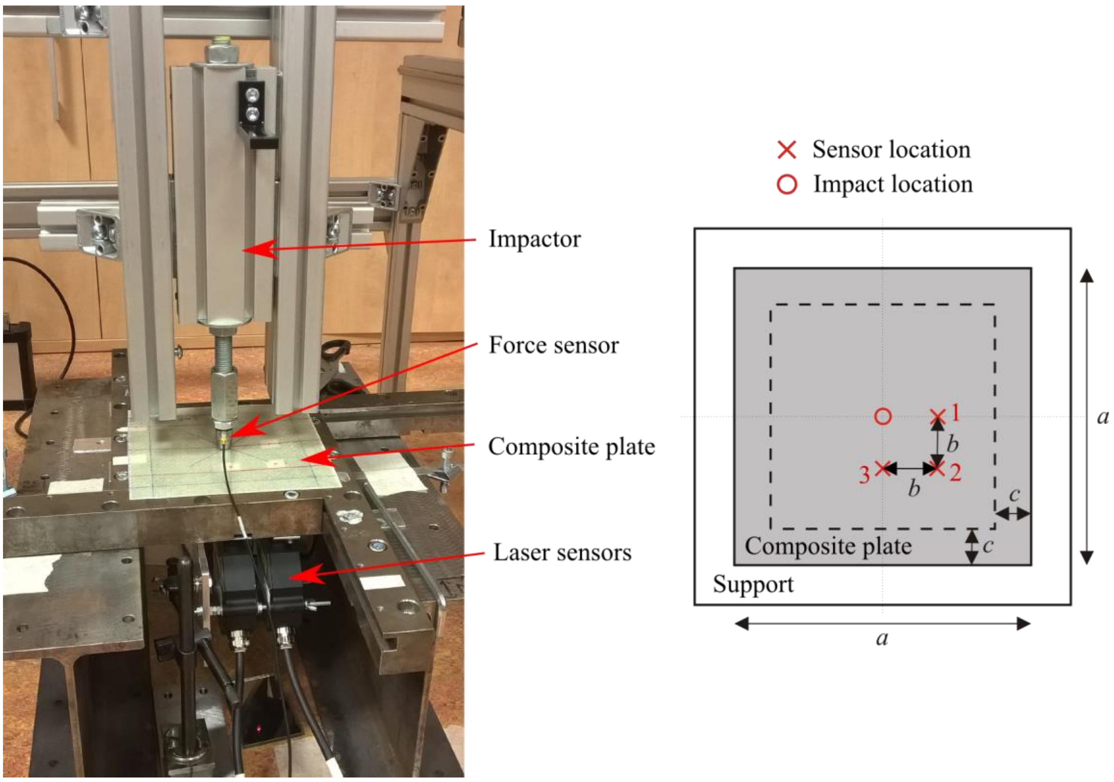

Fig. 1 Photograph (left) and schema (right) of the experimental setup

Table 1 Important dimensions of the experiment

Dimensions	*a*	*b*	*c*	*t*
[mm]	190	40	20	0.9

The impact velocities were continuously increased from initial impact velocity $v = 1$ m/s to the final velocity $v = 4$ m/s with constant step of 1 m/s. First damage of matrix, limited to the area under the tip of impactor, occurred for the impact velocity *v* = 2 m/s. Two measurements were performed for that impact velocity to verify influence of the induced damage on the sensors responses. The responses for both measurements was almost identical (see Figure 3). Damage evolution from the plate center in the diagonal directions was observed for impact with velocity *v* = 4 m/s. Overview of measured data is shown in *Fig. 3*.

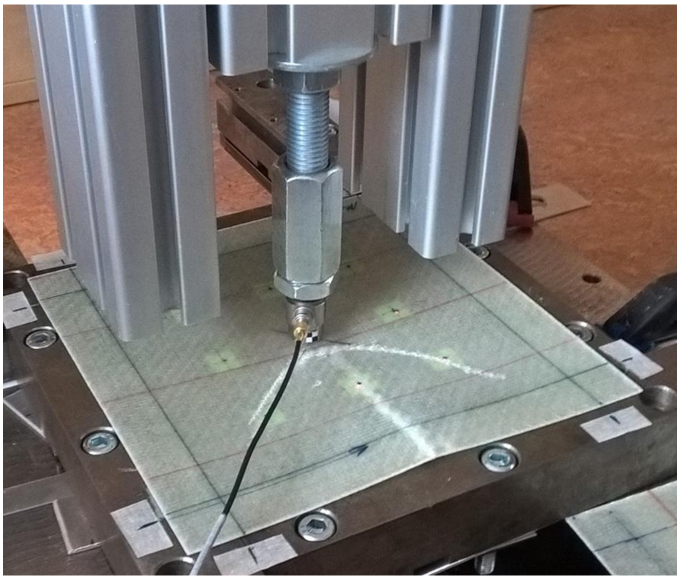

Fig. 2 Composite plate after impact with impact velocity 4 m/s

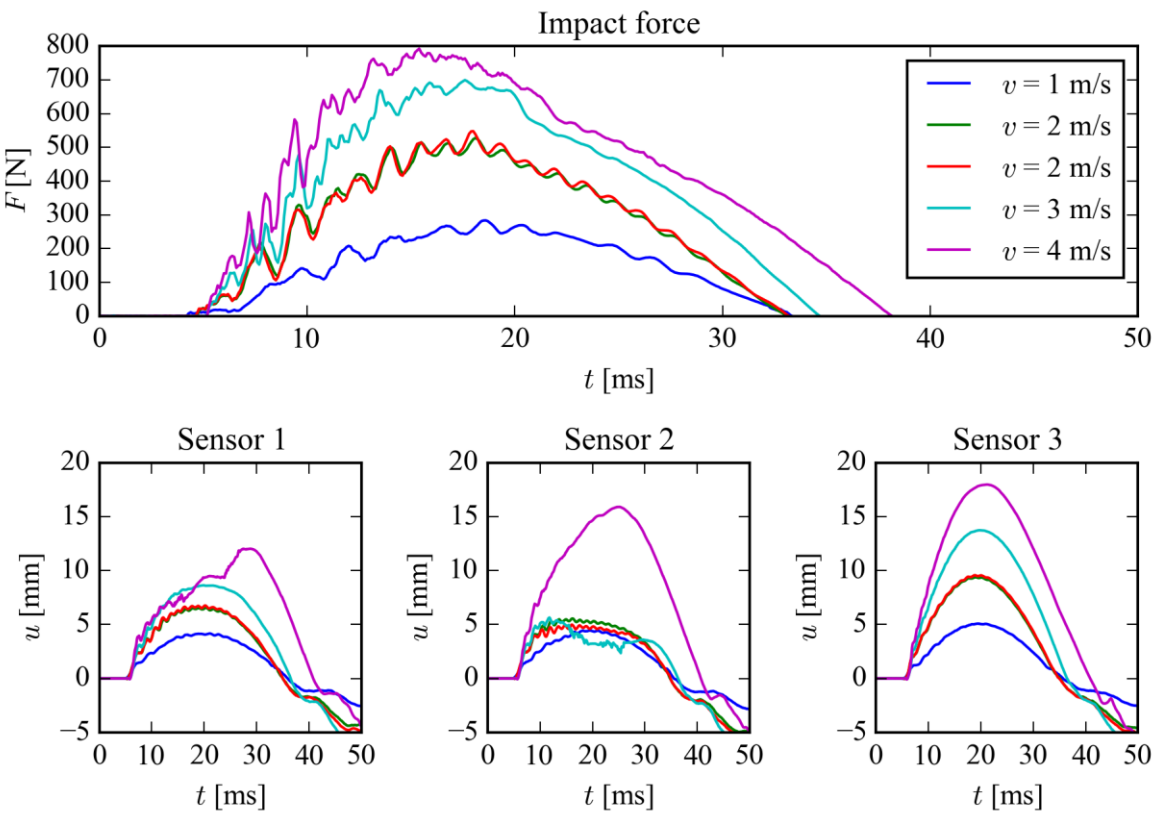

Fig. 3 Measured data

Identification of impact force

The measured data were used for the identification process. The impulse responses and corresponding residuals were determined from the first two measurements, where measured impact force and sensor responses were used. From the values of residual (Eq. 5) shown in *Table* is clear that the worst value is for sensor 2, where the estimated impulse response does not fit both measurements, which can be caused by non-linear response of the sensor. Therefore, sensor 2 was not used for the impact force identification.

Table 2 Residuum for impuse response idnetification for individual sensors

Sensor	1	2	3
Residuum r [mm]	9.17	16.15	4.79

Remaining measurements were used for the impact force identification, where measured sensor responses and determined impulse responses were used. Comparison of identified and measured impact forces are shown in *Fig. 4* and calculated identification error is shown in *Table* .

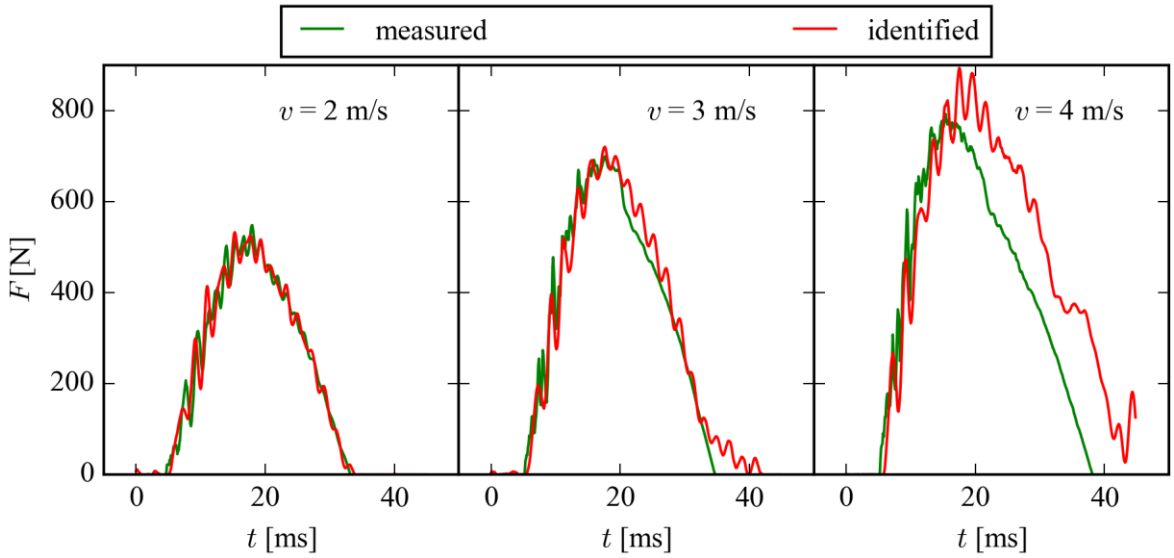

Fig. 4 Comparison of measured and identified impact forces.

Table 3 Identification error

Impact velocity v [m/s]	2	3	4
Identification error [%]	5.93	6.53	17.86

From the results it can be concluded, that impact force was identified with good agreement to measured one for tests with the damage localized under the impact area (v = 2 m/s and v = 3 m/s). For impact with the highest impact velocity, the correspondence is acceptable only up to impact force peak value. Then, the identified force is overestimated due to high responses of sensors caused by loss of stiffness in the significantly damaged areas.

Identification procedure can be therefore used in SHM system for estimation of applied loading up to certain level, when the significant damage of constriction is expected. Exceed of that level can be trigger for the monitoring system to raise warming message and to activate other procedures to characterize the damage extent.

Determination of damage extent directly form the identified impact force is problematic. Numerical model can be used to estimate delamination area for impacts when the identified force correspond well with the applied one. For impacts with higher energies, when the damage significantly influence linearity of sensor responses and therefore the identified force does not correspond to applied one, other methods of SHM can be utilized like guided Lamb waves [6].

Conclusions

Impact force identification procedure was applied on the rectangular composite plate which was experimentally impacted by drop weight mass with various impact velocities. Suitability of displacement sensors was characterized and one of the sensors was excluded from the identification process. Identified impact forces are in good agreement to measured one for two tests where no significant damage occurred. For the last test with the highest impact velocity, the identified force correspond only to the peak value of measured impact force and then is overestimated.

From the results it can be concluded that the identification procedure can be used for decision of exceeding of critical loading on construction. On the other hand, estimation of damage extent from identified force is problematic because the impact force is not correctly identified after occurrence of significant damage.

References

[1] ATOBE, S., SUGIMOTO, S., HU, N., FUKUNAGA, H. Impact damage monitoring of FRP pressure vessels based on impact force identification, *Advanced Composite Materials,* 2014, vol. 23(5–6), pp. 491–505.

[2] BARTOŠEK, J. Identification and localization of impact force on composite structure (in Czech), *Doctoral dissertation,* University of West Bohemia in Pilsen, 2016.

[3] BARTOŠEK, J., KROUPA, T., SMOLÍK, L. Numerical model of composite airfoil segment with piezoelectric sensors. *Materiali in Tehnologije,* 2014, vol. 48(6), pp. 841–845.

[4] BARTOŠEK, J., KROUPA, T., ZEMČÍK, R., LAŠ, V. Optimal sensor distribution for impact loading identification. *In 11th European Conference on Non-Destructive Testing*. Brno: University of Technology, 2014. pp. 1–6.

[5] ZEMČÍK, R., LAŠ, V., KROUPA, T., BARTOŠEK, J.: Reconstruction of Impact on Textile Composite Plate Using Piezoelectric Sensors; *Proceedings of the, Ninth International Workshop on Structural Health Monitoring*, September 10–12, 2013, Stanford University, Stanford, vol. 1, pp. 393–400, ISBN: 978-1-60595-115-7.

[6] ZHONGQING S., LIN Y., YE L., Guided Lamb waves for identification of damage in composite structures: A review, *Journal of Sound and Vibration*, 2006, vol. 295(3–5), pp. 753–780, ISSN 0022-460X.

Acknowledgment

This publication was supported by the project LO1506 of the Czech Ministry of Education, Youth and Sports and by project SGS-2016-038.