Numerical Simulation of the Low-velocity Impact on the Woven Composite Plate by Usage of Hyperplastic Material Model with Damage

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Abstract: The contribution is aimed to the numerical modeling of low-velocity impact and validation of the hyperplastic material model with damage designed by authors for modeling of woven fabric reinforced composites and implemented into commercial FEM software Abaqus. The composite plates were subjected to the low- velocity impact by usage of the drop-test machine with two types of impactor differed by the weight. The experimental data of the tested composite plate in form of deflections at three selected measurement points and the contact force – time dependencies were compared for particular impact velocities with the numerical simulations. The visual comparison of the occurrence of damage on the composite plates was performed and compared with corresponding damage results obtained from the computational model.

Keywords: low-velocity impact; drop test; damage; elastoplasticity; woven composite.

1 Introduction

The composite materials experienced an increased application in various manufacturing industries in the last time such as transport or renewable energy industry due to its specific advantages as decreased weight and high stiffness in comparison with conventional materials. The main disadvantage of the composite materials and its applications is its susceptibility to damage and subsequent failure, which may occur during the life-time of the composite construction. A special chapter of the loading states on the composite constructions are the impact events with the foreign object, such as the bird strike, fall of the different objects such as cell phones or screwdrivers during the inspection or maintenance, or the hits of the small objects such as the flying stones from the tires. The impact event is generally classified as low-velocity, medium velocity and high-velocity impacts [1]. The low-velocity impacts, when the energy of the impactor is fully absorbed by the material of the impacted body, appear to be the most dangerous for the safety and the further life-time of the composite structure [2]. The typical for the low-velocity impacts is causing of internal damages, which causes substantial strength reduction due to cracking of the matrix, fiber splitting or yarn locking [3]. Therefore it is necessary to be able to predict initiation of the damage and its propagation using the numerical simulations in the design part of the composite structure and to include the common cases of low-velocity impacts into the expected loading with regard to the specific application.

2 Tested material and material model

The user defined hyperplastic material model with damage was used for description of the non-linear behavior of the woven fabric reinforced composites [4]. The proposed orthotropic material model is based on thermodynamic principles in accordance of the first and second law of thermodynamics. The model assumes the finite strain theory and considers the additive decomposition of the total logarithmic strain tensor to the elastic and the plastic part [5]. The description of the damage states in the material model is realized by proposed degradation functions that are dependent on the relevant elastic strains. The equations of the damage evolution are applied in the material model in accordance with the principles of continuum damage mechanics [6]. The author's material model is implemented into commercial FEM software Abaqus 6.13 using UMAT and VUMAT subroutines that allows the usage both implicit and explicit solver. The subroutines are written in Fortran code.

The tested woven composite material was made from three layers of fiberglass fabric with plain weave pattern (density 812 g/m^2) and epoxy resin with designation MGS 385 LR. The total thickness of tested woven composite structure was 0.9 mm. Experimental compressive and cyclic static test were performed on the material specimens in accordance of ASTM standards. The mathematical optimization was used in the identification process of material parameters of tested composite. The material parameters are summarized in Tab. 1 and Tab. 2 [4].

Tab. 1: Elastic and strain/hardening curve parameters.

E_{11} [GPa]	E_{22} [GPa]	E_{33} [GPa]	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]	ν_{12} [-]	ν_{23} [-]	ν_{31} [-]	R_0 [MPa]	K_R [MPa]	n_R [-]
25.30	25.79	8.00	4.50	4.50	2.75	0.337	0.337	0.280	35	265	0.4

Tab. 2: Material damage parameters, units [-].

$\varepsilon^0_{11_T}$	$\varepsilon^0_{11_C}$	$\varepsilon^0_{22_T}$	$\varepsilon^0_{22_C}$	$\varepsilon^0_{33_T}$	$\varepsilon^0_{33_C}$	γ^0_{12}	γ^0_{23}	γ^0_{13}
0.0030	0.0007	0.0040	0.0076	0.0	0.0076	0.0048	0.0	0.0
$\varepsilon^R_{11_T}$	$\varepsilon^R_{11_C}$	$\varepsilon^R_{22_T}$	$\varepsilon^R_{22_C}$	$\varepsilon^R_{33_T}$	$\varepsilon^R_{33_C}$	γ^R_{12}	γ^R_{23}	γ^R_{13}
0.0084	0.0500	0.0060	0.0500	0.0001	0.0500	0.0102	0.0001	0.0001
$\varepsilon^F_{11_T}$	$\varepsilon^F_{11_C}$	$\varepsilon^F_{22_T}$	$\varepsilon^F_{22_C}$	$\varepsilon^F_{33_T}$	$\varepsilon^F_{33_C}$	γ^F_{12}	γ^F_{23}	γ^F_{13}
0.0125	0.2000	0.0137	0.2000	0.0233	0.2000	0.0391	0.0350	0.0350
a_{11_T}	a_{11_C}	a_{22_T}	a_{22_C}	a_{33_T}	a_{33_C}	a_{44}	a_{55}	a_{66}
0.0125	0.2000	0.0137	0.2000	0.0233	0.2000	0.50	0.50	0.50
b_{11_T}	b_{11_C}	b_{22_T}	b_{22_C}	b_{33_T}	b_{33_C}	b_{44}	b_{55}	b_{66}
0.0	10.0	0.0	10.0	100.0	10.0	100.0	100.0	0.8550
$K^0_{11_T}$	$K^0_{11_C}$	$K^0_{22_T}$	$K^0_{22_C}$	$K^0_{33_T}$	$K^0_{33_C}$	K_{44}	K_{55}	K_{66}
1.0	1.0	1.0	1.0	0.0	1.0	0.0	0.0	0.76
$D^U_{11_T}$	$D^U_{11_C}$	$D^U_{22_T}$	$D^U_{22_C}$	$D^U_{33_T}$	$D^U_{33_C}$	D^U_{44}	D^U_{55}	D^U_{66}
0.1290	0.7500	0.1210	0.75	1.0	0.75	1.0	1.0	1.0
D^U_{12}	D^U_{13}	D^U_{23}	$D^{\max}_{ij_T}$	$D^{\max}_{ij_C}$				
1.0	1.0	1.0	1.0	0.75				

3 Experiment – low velocity impact

A drop-test machine designed by authors was used for the realization of impact testing of the square specimens made from tested woven composite with dimensions 190 $\times$ 190 mm. The composite specimens were supported by the steel stand along the all edges. The overlap between the plate's edges and the steel stand was 20 mm at each side. The geometry of the tested square plate and its placement on the steel stand is shown in Fig. 1. The three laser sensors OptoNCDT 2200 were used for the measuring of the response of the tested body during the impact event. The position of the selected points for the laser sensors placement is shown in Fig. 1. Due to the width of the vertical linear guides of the drop-machine and compact dimensions of the plate the laser sensors had to be placed under steel stand and square plate. The impact point was in the middle of the plate. The linear guides caused the clearance of impactor in approximate value 3 mm in the horizontal plane that could shift the impact point off the centre of the composite plate. Two types of impactors with different weights (0.243 kg and 2.335 kg) were used for the impact testing. The impactors were guided by the vertical linear guides of the drop-test machine and were accelerated only by the gravity.

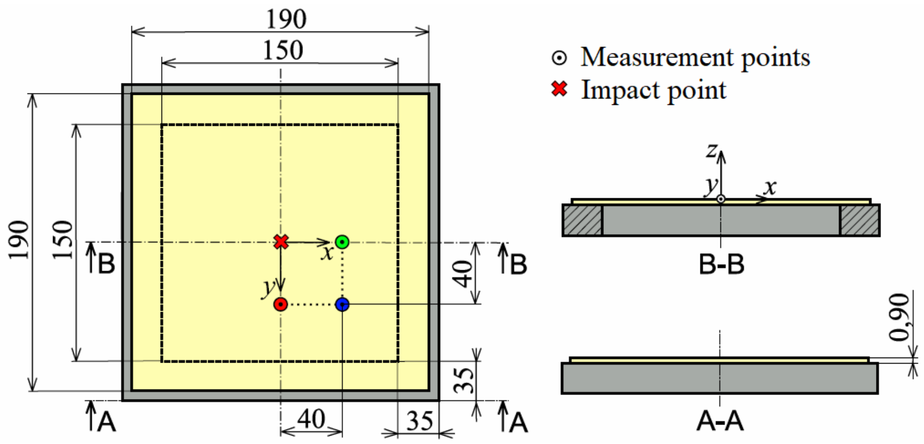

Fig. 1: The geometry of the tested woven composite square plate and the location of the laser sensors in the measurement point during the impact testing.

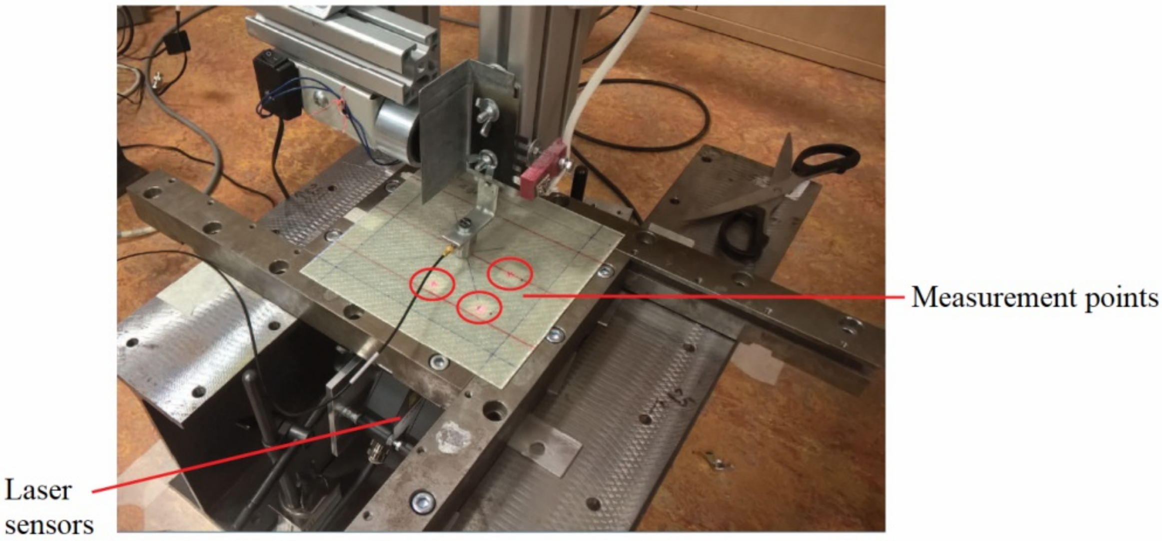

Fig. 2: Experimental apparatus with the woven composite plate and 0.243 g weight impactor.

The impact velocities were varied in the range from 1 to 4 m/s in case of 0.243 kg weight impactor and from 2 to 4 m/s in case of 2.335 kg weight impactor respectively. The step in the ranges of the impact velocities was for the both impactors the same, 1 m/s. The electro-mechanical brake of the impactor based on the principle of the optical gate was always activated during the impact after the first contact event of impactor with the tested composite plate. That avoided the other contact events of impactor with the composite plate and minimized the possibility of the accumulation of the damage in the structure or the occurrence of the secondary damage of the tested plate. The contact force between the impactor and the tested woven composite plate was recorded during the impact events by the force sensor Kistler 9712 B, that was built into the head (spherical shape of the head with radius r = 15 mm) of the impactor. The sampling rates for the laser sensors and the force sensor was 10 kHz. The experimental apparatus for the case of the 0.243 g weight impactor is presented in Fig. 2. The impact events were recorded by the high speed camera Olympus i-Speed 2 with the frame rate 2,000 fr/s. The records were used to other analysis of the behavior of the woven composite plates and investigation of the occurrence of the damage during the loading.

4 Numerical simulations and the results

The numerical simulations of the impact event were performed in the FEM software Abaqus using the authors defined hyperelastic material model with damage, explicit solver based on central difference scheme for time integration and finite strain theory. The computational model was created as a full contact problem of three bodies – composite plate, impactor and steel stand. The friction between bodies has been neglected. The complex geometry of the both types of impactors was simplified and only the spherical head of impactor with added mass to reach the total weighs were modeled. The attached cable from force sensor in the impactor head has been neglected.

The position of the laser sensors in the measuring points is invariable in the plane of the composite plate in the coordinate systems during the impact events, while the location of the nodes of the computational mesh is changed due to deformation of the composite plate during the impact. Therefore the values in form of deflections (z location) of the composite plate at the selected measuring points were interpolated from the space displacements obtained from the neighborhood nodes of computational mesh. The reason of the interpolations of the deflections in the measuring points of the laser sensors and the differences between interpolated deflection and the deflection from the corresponding node in the initial loading state is for the 2D state illustrated in Fig. 3. The 3D bilinear interpolation method was used; the interpolations and the results were post processed in computing platform Matlab [7].

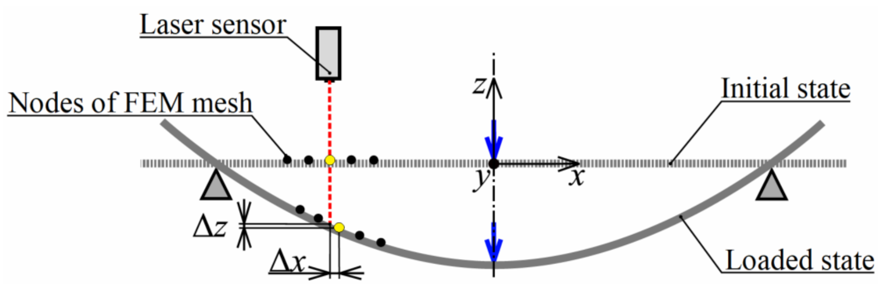

Fig. 3: The principle of the interpolation of the deflection in the measuring points from the space displacements of the neighboring nodes of computational mesh, 2D state of the situation.

The results from numerical simulations and the experiments were for all cases of the impact events compared for the range $t \in \langle 0, 30 \rangle$ ms, when the time $t = 0$ corresponds to the beginning of impact event. The comparison of deflections from the selected measurement points and contact force dependencies on the time is shown for the case of 0.243 kg weight impactor and particular impact velocities in Fig. 4–7. The same scale factor of compared values was used for all impact velocities with the corresponding weight type of impactor. The occurrences of damage were not visually observed on the composite plates in case of impact events with 0.243 kg weight impactor both in the case of numerical simulations and experiment too.

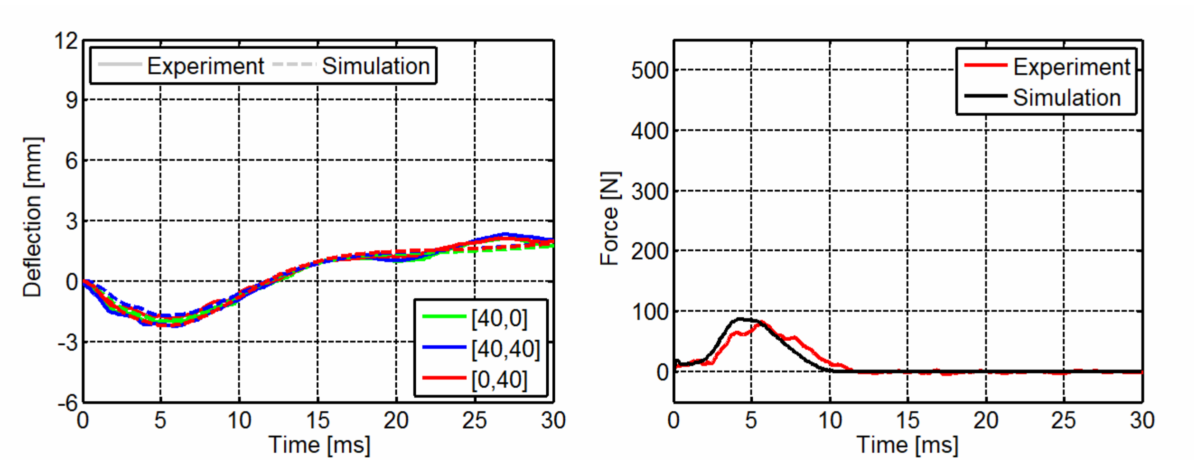

Fig. 4: The comparison of the deflections in measurement points (left) and contact force (right) between experiment and numerical simulation for 0.243 kg weight impactor and impact velocity 1.0 m/s.

The deflections at three measuring points and contact force comparisons between numerical simulations and experiment are shown for the case of 2.335 kg weight impactor and tested range of velocities in Fig. 8–10. The damage occurred during the impact testing only in the case of 2.335 kg weight impactor and only for impact velocity 4.0 m/s both in the experiment and simulation. The comparison of the occurrence of the damage on the composite plate is shown in Fig. 11. It is illustrated in case of numerical simulation on the composite plate using the contour plot of damage in the shear plane 12 (D_66) and damage in material direction 2 in tension

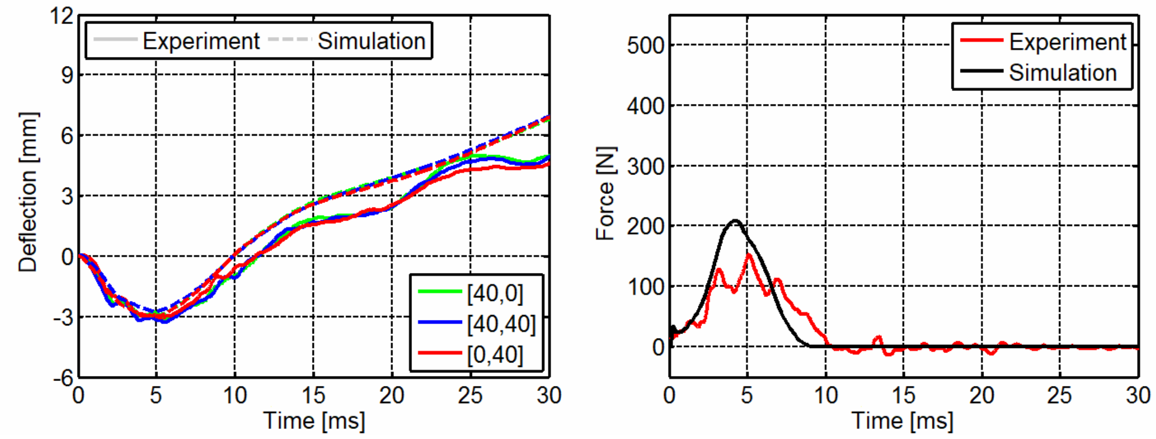

Fig. 5: The comparison of the deflections in measurement points (left) and contact force (right) between experiment and numerical simulation for 0.243 kg weight impactor and impact velocity 2.0 m/s.

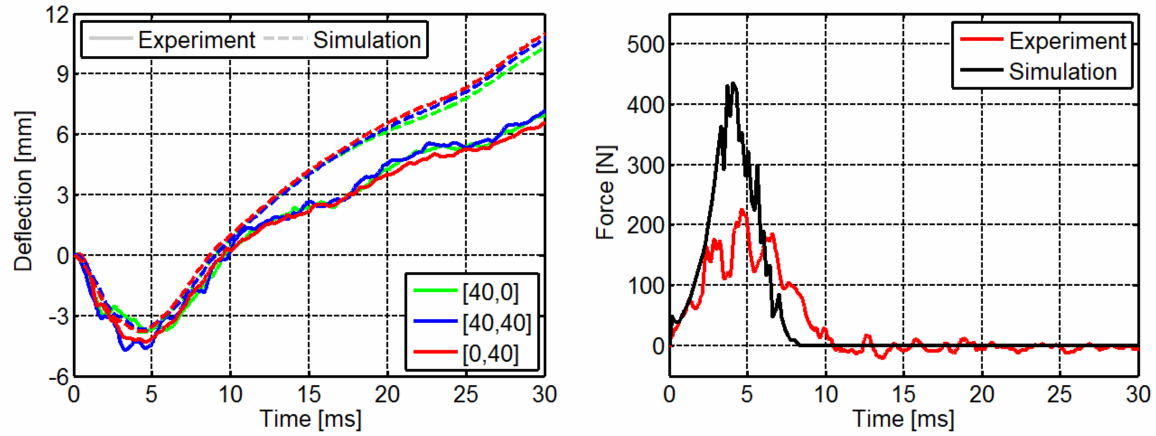

Fig. 6: The comparison of the deflections in measurement points (left) and contact force (right) between experiment and numerical simulation for 0.243 kg weight impactor and impact velocity 3.0 m/s.

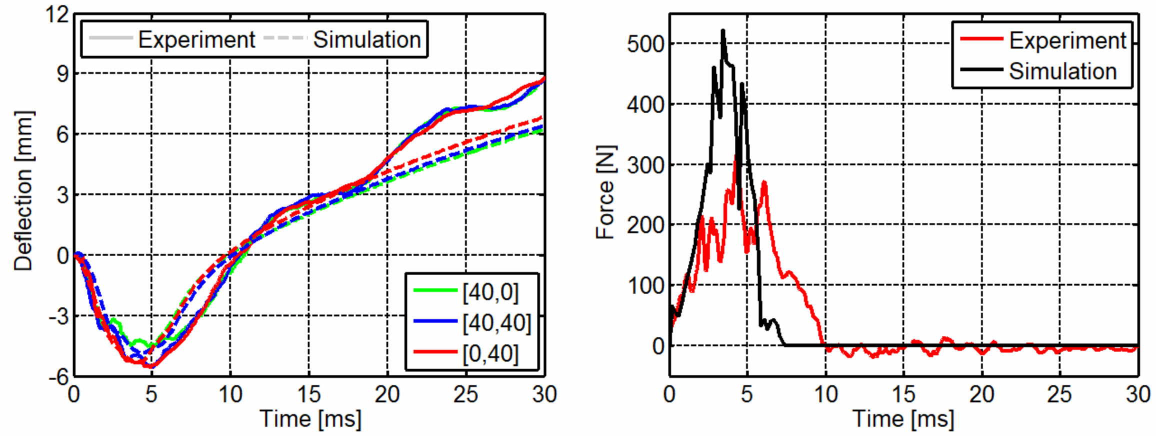

Fig. 7: The comparison of the deflections in measurement points (left) and contact force (right) between experiment and numerical simulation for 0.243 kg weight impactor and impact velocity 4.0 m/s.

(D_22) witch occurred locally in the impact point of the plate. The damage is in the case of experiment evident in the detail picture with the blue border in the Fig. 11.

The comparison of the behavior of the composite plate during the impact testing between the numerical computational model and the pictures obtained from high speed camera during the experiment is shown for the 2.335 kg weight impactor and impact velocity 4.0 m/s in Fig. 12. The maximal deflection is achieved in the time t = 15 ms after the start of impact event at t = 0 ms.

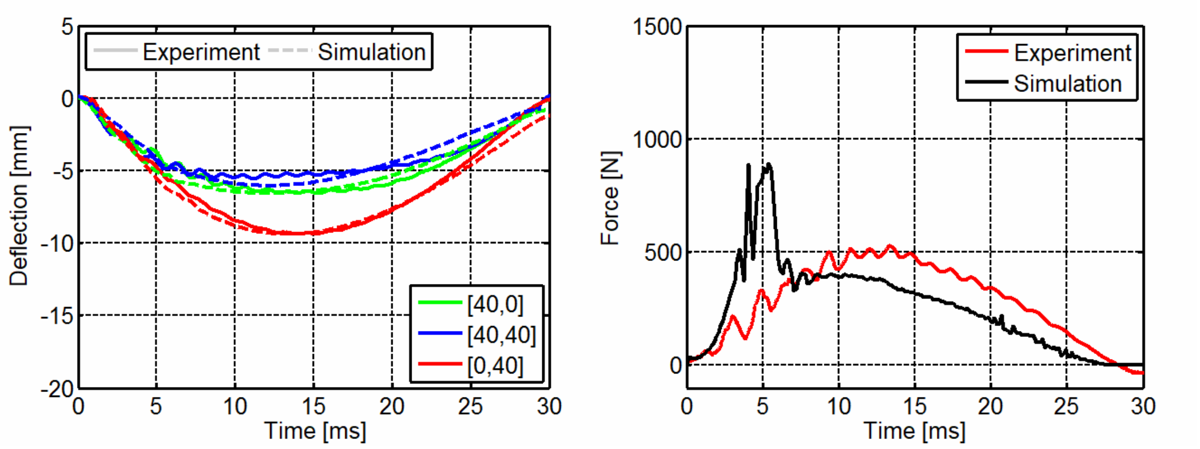

Fig. 8: The comparison of the deflections in measurement points (left) and contact force (right) between experiment and numerical simulation for 2.335 kg weight impactor and impact velocity 2.0 m/s.

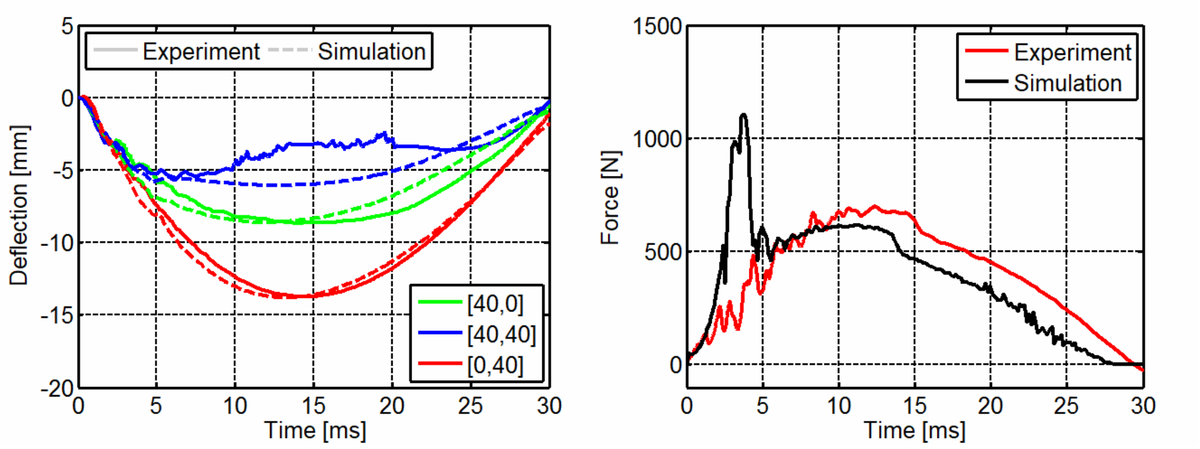

Fig. 9: The comparison of the deflections in measurement points (left) and contact force (right) between experiment and numerical simulation for 2.335 kg weight impactor and impact velocity 3.0 m/s.

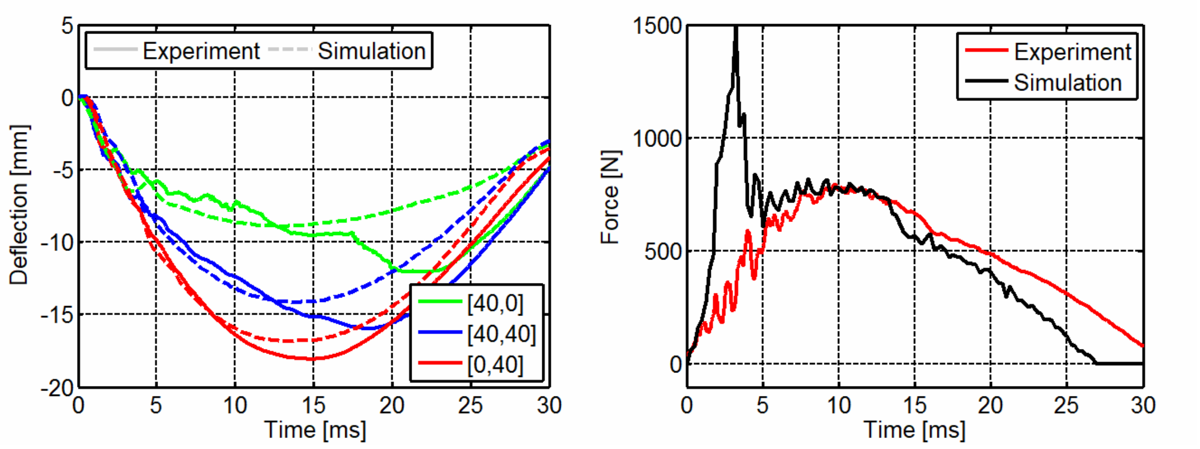

Fig. 10: The comparison of the deflections in measurement points (left) and contact force (right) between experiment and numerical simulation for 2.335 kg weight impactor and impact velocity 4.0 m/s.

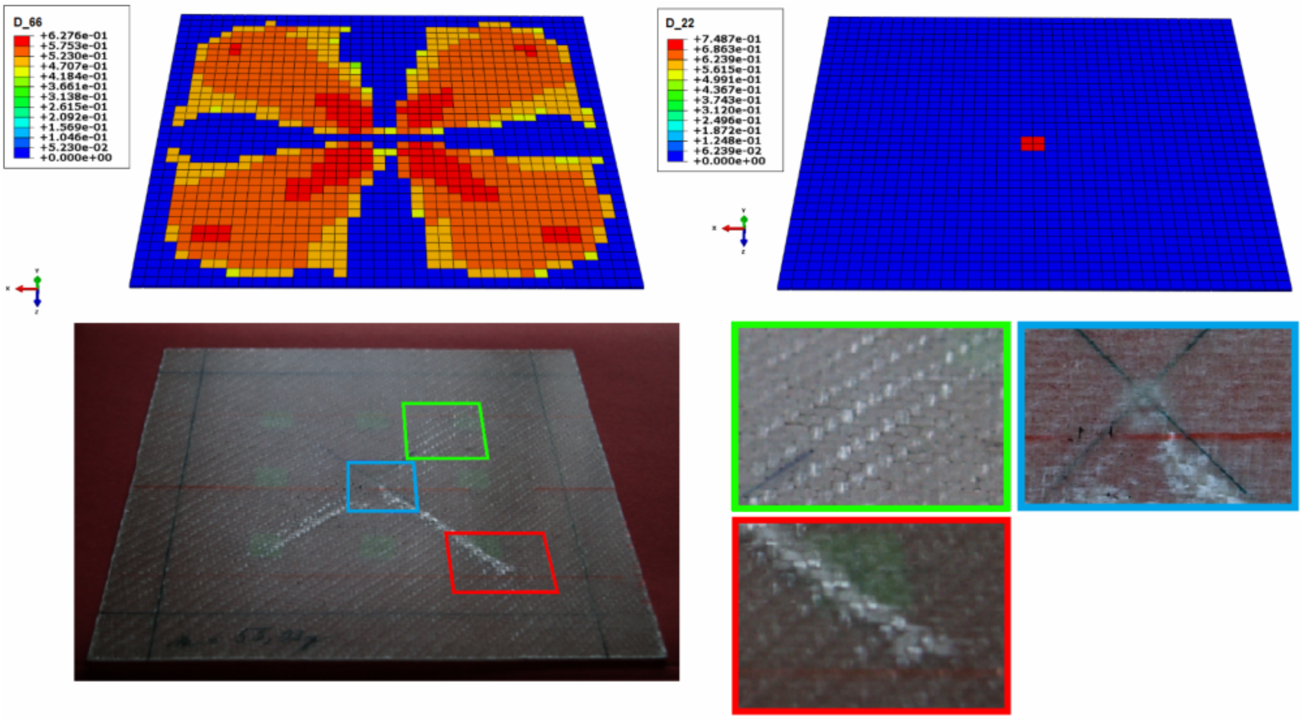

Fig. 11: The comparison of damage of the composite plate subjected to low-velocity impact with 2.335 kg weight impactor and impact velocity 4.0 m/s between numerical simulation and experiment.

5 Conclusions

User defined hyperplastic material model with damage implemented into commercial finite element method software Abaqus was verified using the experiment in the case of modeling of the dynamic events. The response of the composite square plate to low-velocity impact was experimentally investigated using the drop-test machine and two types of impactor with different weights. The deflection-time dependencies, contact force-time dependencies and the occurrence of the damage were compared. Even though the comparison of the deflection-time dependencies from the experiment and numerical simulations shown the good agreement, in the case of low-weight impactor the increasing deviations on the impact velocity in the secondary movements of the plate, i.e. after unloading of the impactor, are evident. The comparison of the contact force-time dependencies shows agreement between numerical and experimental results. However the experimental data did not show the increase of the maximum of the first peak of the contact force-time dependencies in the contrast to the numerical results. These deviations of the contact force dependencies can be caused by neglected friction and damping in contact between spherical head of impactor and composite plate in the computational model, possibly during the experiment there may have been excessive damping of the impactor due to clearance of the impactor in the horizontal plane in the linear guides of the drop-test machine. The visual comparison of the visible occurrence of damage on the composite plate shows the quantitative match with the numerical simulations. However, the damage model predicts the failure, or rupture that was not reached in the experiment.

Acknowledgement

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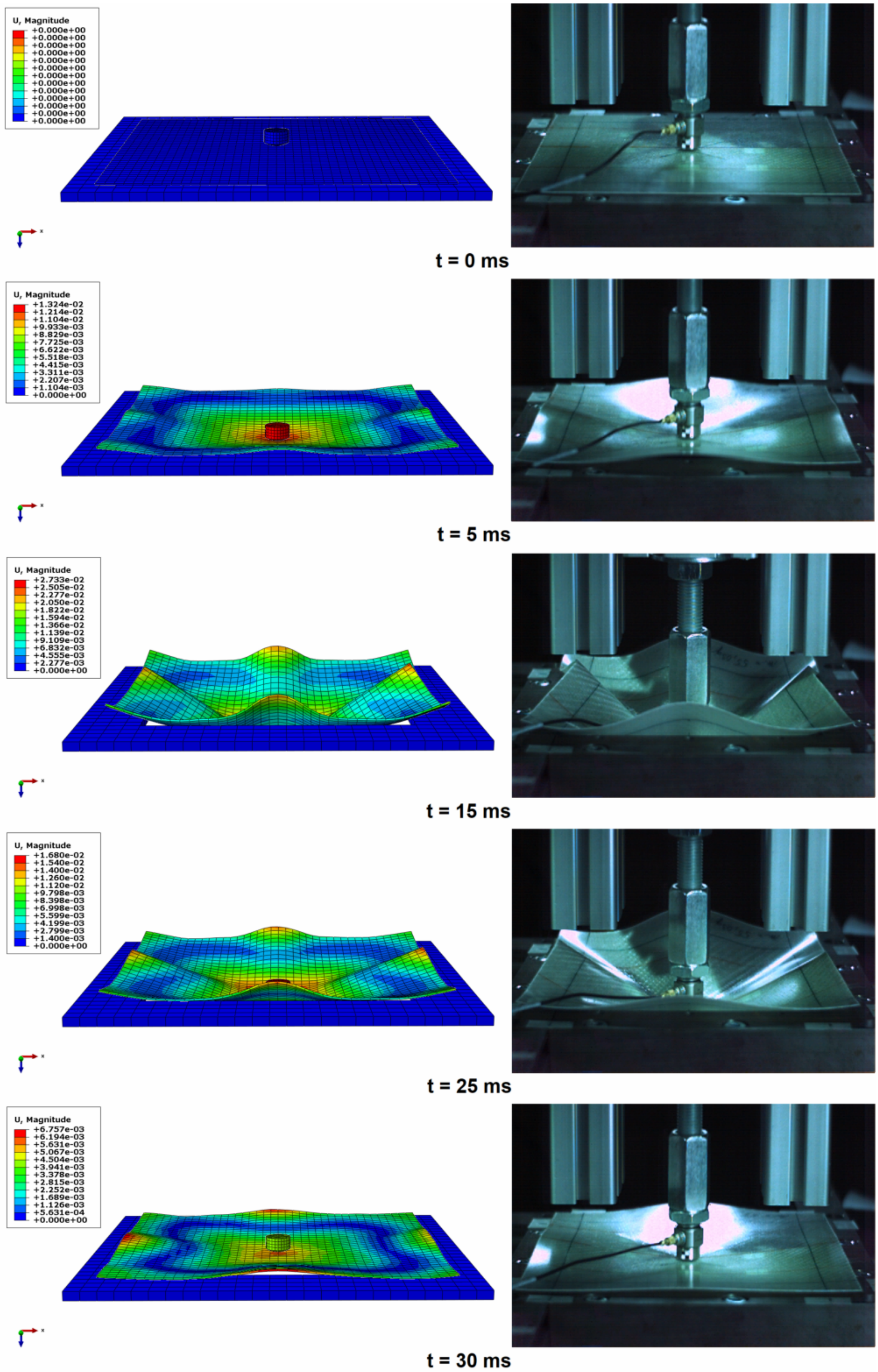

Fig. 12: The comparison of the behavior of the composite plate during the impact testing between the numerical computational model and the pictures obtained from high speed camera during the experiment for the 2.335kg weight impactor and impact velocity 4.0 m/s. The total displacement is presented in the case of numerical simulations.

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