INVESTIGATING THE EFFECT OF STATIC PRELOADS ON THE IMPACT BEHAVIOUR OF HONEYCOMB SANDWICH STRUCTURES

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Abstract

Composite sandwich with honeycomb cores made of phenol resin impregnated paper is widely used in aircraft structures. Owing to the rather weak core material, this kind of sandwich is prone to a range of defects and damages resulting from impact events, which may accidentally occur during the aircraft assembly or operation. Since airframes must be damage tolerant, barely visible impact damages have to be considered in the structural design process. Usually, this damage tolerance evaluation is based on experimental results obtained from low-velocity impact tests on unloaded components. However, in reality aircraft structures are not completely stress free, even if the aircraft is in the parking position. At least the structural weight will cause a permanent static preload.

In order to evaluate the effect of static preloads on low-velocity impact damages an experimental and numerical study was conducted. The results of both investigations showed a significant influence of compressive preloads on the impact behaviour of honeycomb sandwich. Compared to impact damages in unloaded structures even low prestrains result in more severe damages, particularly in the honeycomb core.

1. Introduction

Sandwich is often used as a lightweight design solution for load-carrying components of airplanes and helicopters due to their excellent mechanical properties such as high strength-to-weight and stiffness-to-weight ratios. This is particularly true for sandwich with face sheets made of carbon fibre reinforced plastics (CFRP) and non-metallic honeycomb cores [1]. Owing to the rather weak core material, this kind of structure is prone to a range of damages resulting from impact loading that may accidentally occur during aircraft assembly or operation. These damages and their effect on the load carrying capability of the structure have to be considered in the damage tolerant design of airframes. Currently, the standard design procedure is based on experiments carried out on unloaded structures. However, in reality even on the ground aircraft structures are not completely stress free because at least the structural weight will cause a permanent static preload. Structural preloads will be even higher during take-off and landing, where the probability of foreign object impacts is rather high.

Whereas the impact behaviour of unloaded sandwich has been investigated extensively [e.g. 2-6], up to now only few research papers have been published on the effect of impact events on loaded components. Most of these deal with experiments at high impact velocities [e.g. 7, 8]. In [9] an analytical dynamic model was presented, which provides the time dependent stress state in a preloaded composite sandwich resulting from low-velocity impacts. However, in this approach the core is assumed to be homogenous, which prevents the application to discrete cores such as honeycombs. Since no failure criteria are included in the model, also no information on the damage initiation and growth is gained. Therefore, the application on real honeycomb sandwich structures is rather limited.

The aim of the research presented in the current paper has been to reduce the knowledge gap regarding the influence of prestresses on the impact behaviour of honeycomb sandwich structures under low velocity impact conditions. For this purpose both, an experimental and numerical study was carried out. In the experimental phase, uniaxial compressive preloads were applied to samples with different sandwich configurations, which were subsequently impacted in the stressed state at low velocities. After impact the damage size and intensity was determined using NDT methods. In the second phase, a numerical simulation model was developed to investigate the failure process inside the sandwich structure. In order to get reliable results, numerical methods applied for this task have to be based on close to reality models of the structure. Particularly, local impact damage can be assessed only when the complete honeycomb core is modelled with finite shell elements [10, 11]. Using such a simulation model, the effect of various compressive preloads on the structural performance was systematically investigated.

2. Experimental Analysis of the Impact Behaviour of Preloaded Honeycomb Sandwich

The research program commenced with an extensive test campaign on honeycomb sandwich structures. The aim was to characterize the impact behaviour of different sandwich configurations under compressive preloads (Figure 1).

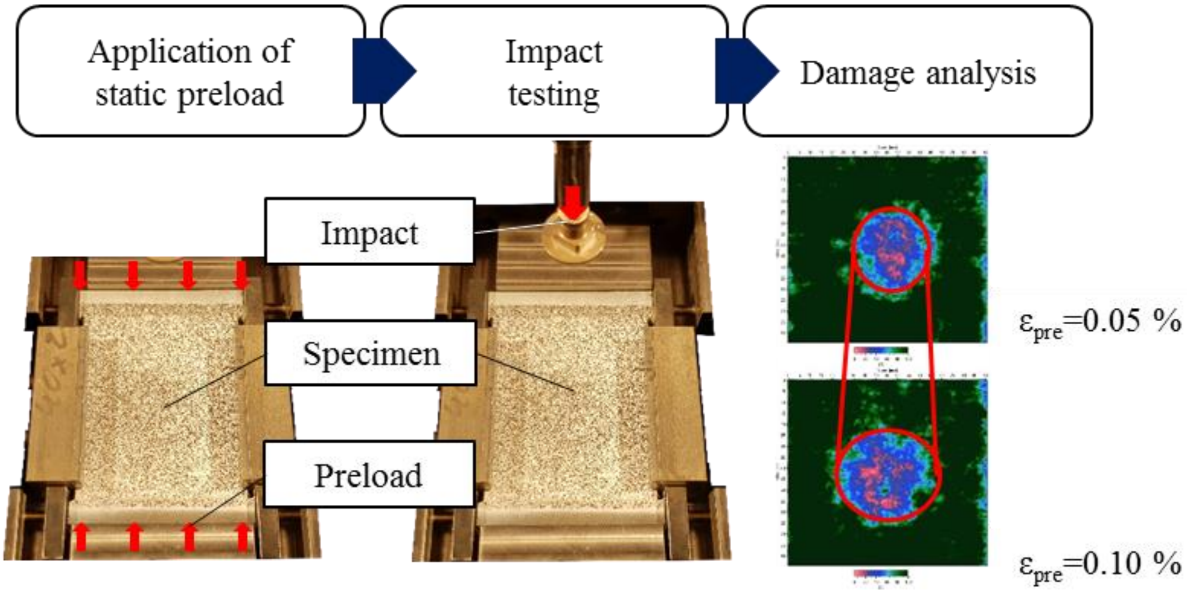

Figure 1. Procedure for impact tests on prestressed honeycomb sandwich structures

The experimental program started with the calibration of the loading rig by applying uniaxial compressive forces on test specimens at different stress levels. Achieved results were the load-strain curves for each of the sandwich configurations investigated. These data have been used to determine the load levels which are required to induce defined prestrains. After calibration the sandwich samples were loaded up to the specified strain level and then impacted at several energy levels. Finally, the impact damage areas were analysed using an ultrasonic measuring method. Results gained were the contact-force-time histories depending on the prestrain level, the remaining impact dent depth and the in-plane and out-of-plane extent of the skin and core damage.

2.1. Sandwich Test Configurations

The test program included several sandwich configurations. The core of the specimens consisted of Nomex® honeycombs with 3.2 mm and 4.8 mm cell widths and densities of 48 kg/m³ and 32 kg/m³, respectively. As sandwich skin material both unidirectional as well as woven CFRP fabric plies (Hexcel M18/1-G939 and M18/1-G947) were considered. Depending on the face sheet layup, specimens with a skin thickness between 0.8 mm and 1.8 mm were used. Skins in this thickness range are typical for sandwich applications in aircraft. Before testing, the core material of the specimens was partially removed in the load introduction areas. The resulting space was then filled with epoxy resin. Subsequently, the edges were machined in order to achieve parallel load introduction elements of high quality.

2.2. Preload Test Set-up and Preliminary Investigations

Since the real stress-strain behaviour of the specimens was not previously known, the experimental program started with the calibration of the hydraulic loading rig which was developed at the *Institute of Aerospace Engineering* (Figure 2). For the calibration task samples of each sandwich configuration were loaded by uniaxial compressive forces. The load introduction elements of the rig consist of massive I-beams made from steel to prevent any bending effects. Two hydraulic cylinders on each side of the rig are used to introduce the compressive load. Force transducers are located on the hydraulic cylinders to record the load-time-histories. Lateral simple supports on both sides of the sandwich samples prevent premature buckling. The specimen clamp fixture is shown in Figure 3.

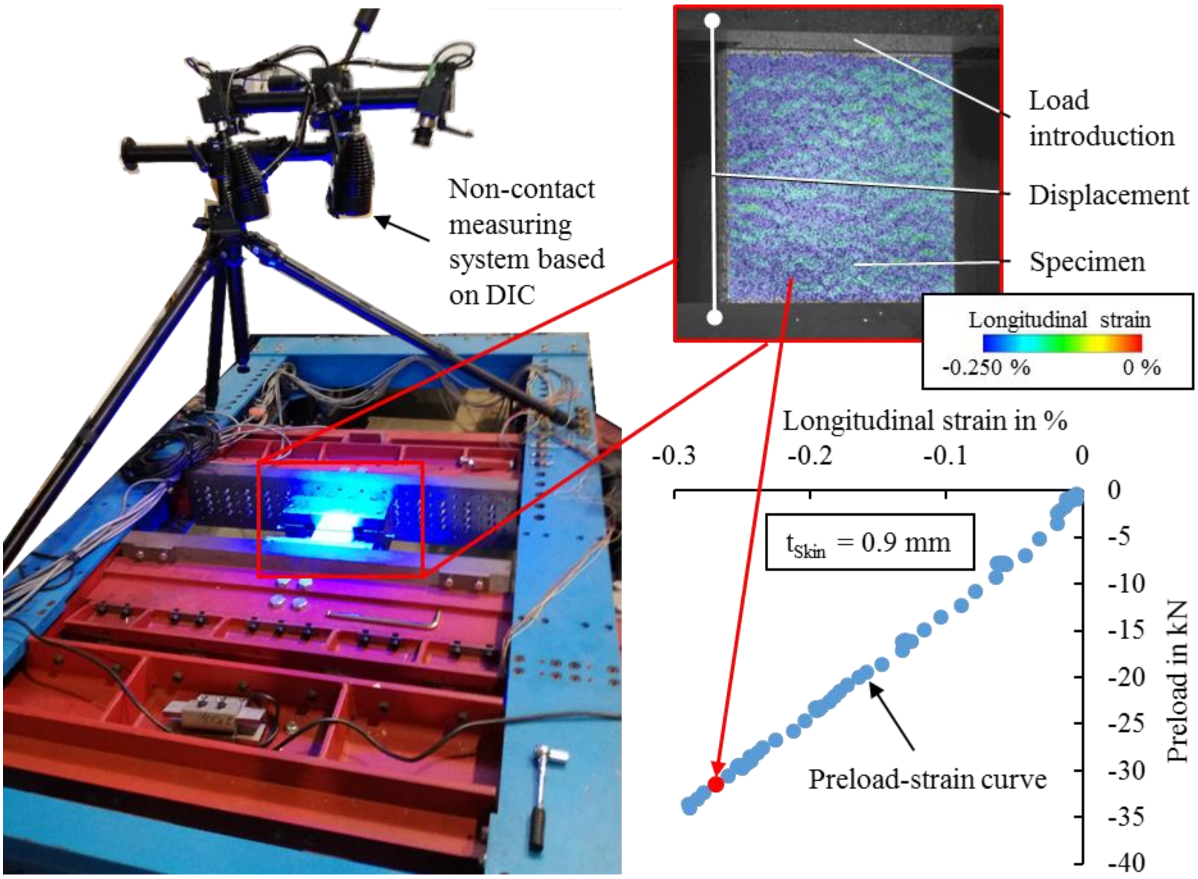

Figure 2. Test set-up for measuring the preload-strain behaviour

In these preliminary experiments, the specimens were loaded up to the structural strength limit of the particular sandwich configuration. During the loading phase the compressive strain was measured on the sandwich face sheets using a non-contact measurement system which is based on a digital image correlation (DIC) technique. Achieved results were the load-strain curves for all sandwich types investigated. The measured load-strain relations proved to be nearly linear as can be seen in Figure 2 for a sample with 0.9 mm thick face sheets. Therefore, a linear load-strain behaviour was assumed for the further investigation.

2.3. Impact Test Set-up and Test Procedure

The impact tests on the preloaded honeycomb sandwich specimens were performed using the test set-up shown in Figure 3. A drop tower was fitted on a steel framework in order to provide sufficient space below for the hydraulic loading rig. The used impactor had a semi-spherical head of 1-inch diameter and a weight of 1.22 kg. Pneumatic rebound brakes prevented an inadvertent second impact. These pneumatic brakes were automatically activated after crossing a photoelectric barrier.

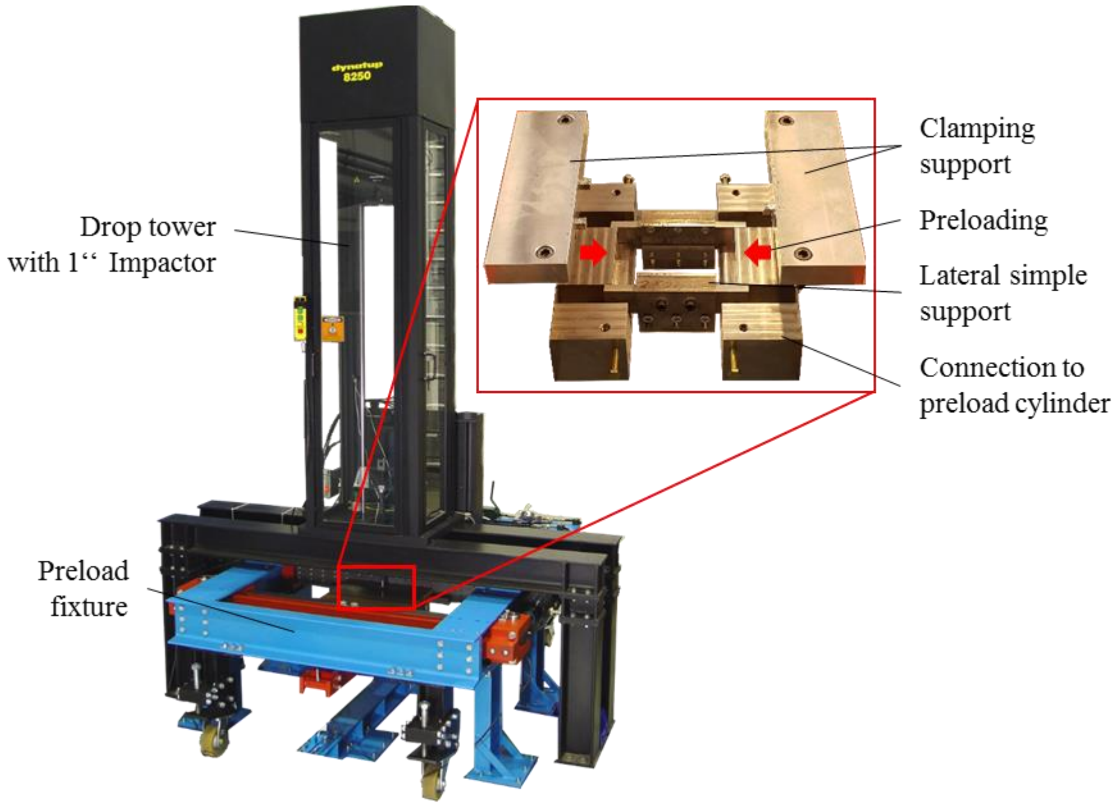

Figure 3. Preload and impact test set-up

The first step of the test sequence was to load the specimen up to the specified compressive strain level which was then kept constant. In the next step the preloaded sample was impacted with the specified energy level. During the whole procedure the applied compressive load as well as the impact force-time history was measured. Table 1 shows an overview of the experimental program carried out on the different sandwich configurations. Examples of the test results obtained are given in Figure 5.

Table 1. Overview of impact and preload test conditions

Face sheet thickness (mm)	*Honeycomb* *cell width* (mm)	*density* (kg/m³)	*thickness* (mm)	*Prestrain* ε_{Pre} *(%)*	*Impact* E_{Imp} *(J)*
0.8 / 0.9 / 1.1 / 1.8	3.2	48	15.0	0.000 0.025 0.050 0.100 0.150	2 / 3.5 / 5
	4.8	32			

2.4. Analysis of Honeycomb Sandwich Failure

After impact the resulting skin delamination and core damage areas were determined by ultrasonic testing using the impulse-reflection-method. Additionally, the dent depth in the impact centre was determined using a digital dial gauge. These measurements were made only after a relaxation period of 48 h. Figure 4 shows typical ultrasonic images of sandwich samples with 0.9 mm thick face sheets, which were preloaded to 3 different compressive strain levels and impacted with 2 Joules. Also, the measured impact dent depths are given for the applied prestrains and 3 different impact energies.

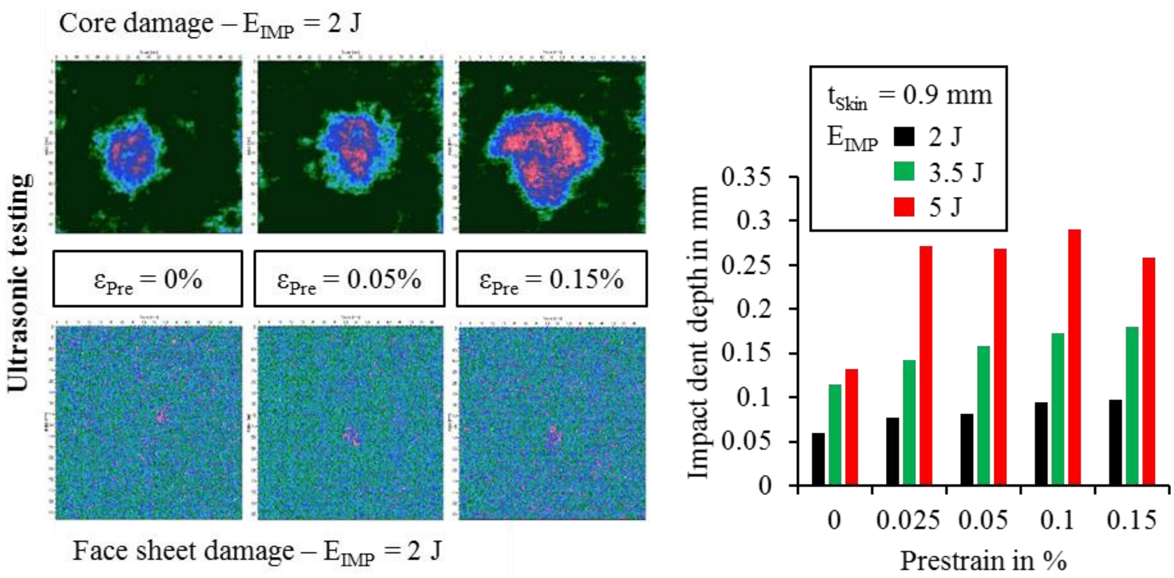

Figure 4. Ultrasonic damage images and dent depths of preloaded honeycomb sandwich structures

The low-velocity impacts resulted in barely visible dents in the face sheets and rather small delamination areas, whereas the damaged core area was quite larger. Therefore, only the core damage was utilized to evaluate the effect of static preloads on the impact behaviour in this research.
It is obvious from Figure 4 that the core damage areas grow considerably with both the impact energy as well as the prestrain level. In contrast the impact dent depths increase only slightly with rising preloads. Consequently, all dents remain barely visible within the range of the investigated preloads and impact energies. Nevertheless, the compressive prestrains are critical because an increasing core damage area affects the load carrying capability of sandwich structures significantly [4].

3. Finite Element Modelling

In the second phase of the research, finite element simulations were carried out to analyse the failure phenomena occurring during low-velocity impacts on prestressed honeycomb sandwich. For this purpose, the nonlinear dynamic solver LS-Dyna was applied.
The detailed finite element models of the sandwich structure were created by a parametric mesh generator called SandMesh [12, 13], which was developed at the Institute of Aerospace Engineering. This code permits to generate fine meshed models of sandwich structures with honeycomb, foam and folded cores. The main advantage of SandMesh is the capability to model detailed honeycomb structures including imperfections [13].
The basic finite element model used for the impact simulation is shown in Figure 5. In addition, the material characteristics of the different model components are given. The local honeycomb cell geometry is based on data provided in [13]. The material properties for the aramid paper as well as for the resin were taken from [10].
The honeycomb cores were modelled by 4-node shell elements for the cell walls and volume elements for the resin corners. The shell elements consisted of three material layers to account for the distribution of paper and resin material over the cell wall thickness as described in [10]. The nonlinear behaviour of the paper was included by a user-defined material law, which was developed at the Institute of Aerospace Engineering and implemented in LS-Dyna. This model considers different stress-strain characteristics under tension and compression loads. It was used for all layers of the core elements including the paper and resin material. The face sheets made of carbon fabric layers were modelled also by 4-node-shell elements with an orthotropic material law. Delamination interfaces were inserted between all face sheet layers using the efficient volume cohesive formulation.

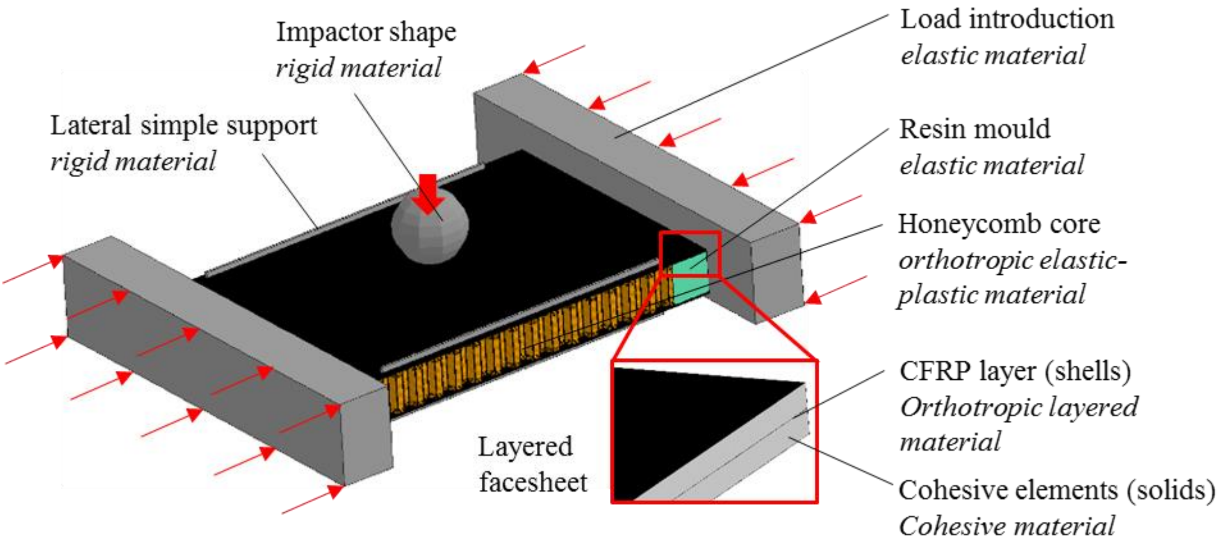

Figure 5. Finite element model for impact simulation

The simulations started with the application of the specified compressive preload by prescribed deformations of the load introduction surfaces longitudinal to the sample. To prevent a premature buckling of the sandwich during this phase supports were added in the model on both sides of the samples (Figure 5).
In the second step, the stress state of the specified preload level was transferred to the impact simulation model. The impactor was modelled using a semi-spherical impactor head of 1 inch diameter and a weight of 1.22 kg.

4. Experimental and Numerical Impact Results

A numerical study was performed to show the applicability of the developed simulation model. Some of the obtained numerical results are shown in Figure 6 in comparison with the experimental data for a sandwich configuration with 0.9 mm thick skins impacted at 2 Joule under different prestrain levels.

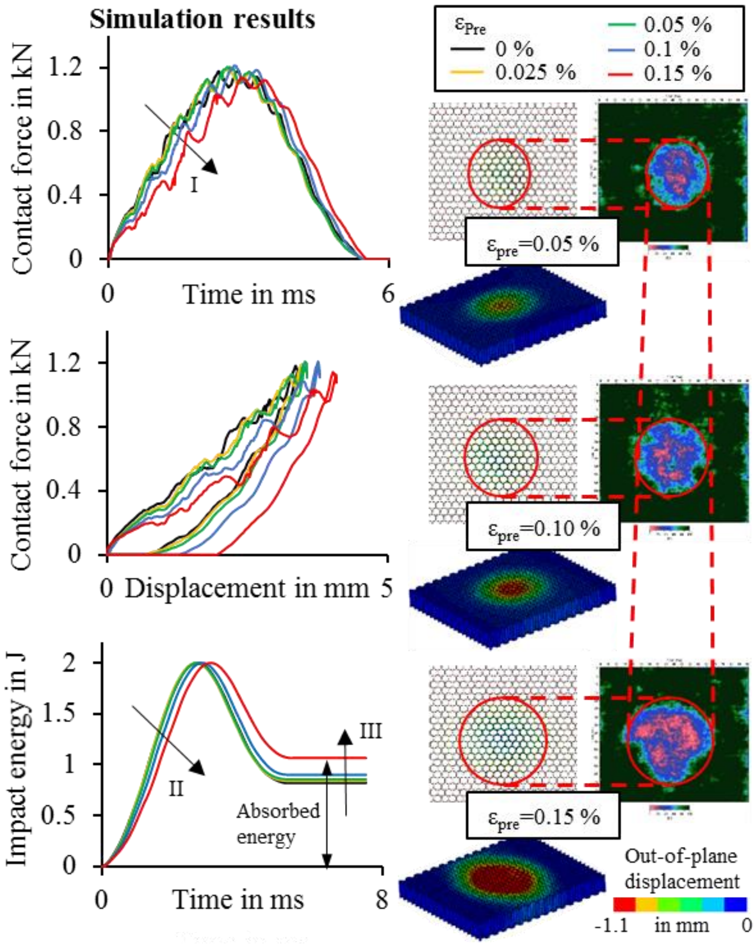

Figure 6. Preloaded impact damage results: comparison of test and simulation

With an increasing prestrain level both the contact force-time as well as the force-displacement curves show a decreasing slope (I), which indicates a growing flexibility. Furthermore, the initial slope of the impact energy-time relation declines (II) and the absorbed energy of the sandwich structure rises (III) with increasing compressive preload. The higher absorbed energy results in a larger damage area in the core as shown by the ultrasonic images (Figure 4). Previous investigations [4] have shown that this core damage significantly affects the structural behaviour of honeycomb sandwich: the larger the damage area, the less the load carrying capability. Also Figure 6 clearly shows that the results of the numerical analysis agree very well with the experimental data.

5. Conclusions

The experimental study performed in the presented research provided a comprehensive database on preload- and impact-force time relations for a range of impact energies and prestrain levels. The data were obtained for several honeycomb sandwich configurations. For the numerical investigations, the nonlinear dynamic solver LS-Dyna was used. This program permits to determine the highly dynamic impact behaviour of sandwich structures very accurately. The effect of static preloads on impact induced damages was evaluated for several compressive prestrain levels. The simulations as well as the experiments revealed that even a low static preload has a considerable effect on the core damage of the investigated honeycomb sandwich configurations. It could be shown that the results obtained by numerical simulation agree very well with the experimental data. Therefore, it can be concluded that the developed simulation model is able to predict the influence of static preloads on extend and intensity of impact damages in honeycomb sandwich structures with good accuracy.

Acknowledgments

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References

[1] A.S. Hermann, P.C. Zahlen, I. Zuardy. Sandwich Structures Technology in Commerical Aviation. *O. Thomson, E.Bozhevolnaya, A. Lyckegaard (eds) Sandwich Structures 7: Advancing with Sandwich Structures and Materials*, 7:13-26, 2005.
[2] S. Abrate. Soft impacts on aerospace structures. *Progress in Aerospace Sciences*, 81:1-17, 2016.
[3] Y. Chen, H. Shujuan, K. Fu, X. Han, L. Ye. Low-velocity impact response of composite sandwich structures: Modelling and experiment. *Composite Structures*, 168:322-334, 2017.
[4] C. Fischer, F. Hähnel, A. Hauffe, K. Wolf. Strategies to investigate the residual strength of impact damaged honeycomb sandwich structures using detailed numerical models. *21th International Conference on Composite Materials, Xi'an, China,* August 20-25 2017.
[5] M. Elamin, B. Li, K.T. Tan. Impact damage of composite sandwich structures in arctic condition. *Composite Structures*, 192:422-433, 2018.
[6] M.J. Weber, C. Fischer, F. Hähnel. Nonlinear modelling and characterisation of PMI-based foam core materials for FRP sandwich structures, *3rd International Conference on Mechanics of Composites, Bologna, Italy,* July 7-4 2017.
[7] M. D. Rhodes. Impact Fracture of Composite Sandwich Structures. *AIAA / ASME / SAE 16th Structures, Structural Dynamics, and Materials Conference*, Denver, Colorado, May 27-29 1975.
[8] D. M. McGowan, D. R. Ambur. Structural Response of Composite Sandwich Panels Impacted with and without Compression Loading. *Journal of Aircraft*, 36:596-602, 1999.
[9] K. Malekzadeh, M. R. Khalili, R. K. Mittal. Response of In-plane Linearly Prestressed Composite Sandwich Panels with transversely flexible Core to Low-velocity Impact. *Journal of Sandwich Structures and Materials.* 8:157-181, 2006.
[10] F. Hähnel. Ein Beitrag zur Simulation des Versagens von Honigwaben aus Meta-Aramid-Papier in schlagbelasteten Sandwichstrukturen. *Dissertation, Shaker Verlag, Dresden,* 2016.
[11] R. Seemann, D. Krause. Numerical Modelling of Nomex honeycomb sandwich cores at meso-scale level. *Composite Structures,* 159:702-718, 2017.
[12] C. Fischer, F. Hähnel, A. Hauffe, K. Wolf. Influence of Imperfections on the structural behaviour of honeycomb cores. *17th European Conference on Composite Materials, Munich, Germany,* 2016.
[13] M. Streubig, K. Wolf. Sand-Mesh^{Plus} – A Parameter Controlled Finite-Element Pre-processor for Composite Sandwich Structures. *Proc. of the 1st CEAS European Air and Space Conference, Berlin, Germany,* 1:2227-2232, 2007.