INFLUENCE OF IMPERFECTIONS ON THE STRUCTURAL BEHAVIOUR OF HONEYCOMB CORES

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Keywords: Sandwich, honeycomb cores, imperfections, numerical simulation

Abstract

Honeycomb cores made of phenol resin impregnated paper are widely used in sandwich structures. When employed in aircraft these structures have to be damage tolerant. This means damages have to be considered in the design process. For the damage tolerance analysis experiments are increasingly replaced by numerical simulation using explicit finite element solver. Since the most critical damages in sandwich structures are caused by the impact of foreign objects, related simulation models have to include the detailed geometry of the honeycombs. Usually, finite element models of this kind of cores are based on an ideal hexagon geometry with flat walls of constant thickness. Real honeycomb cores clearly differ from that. In order to investigate the extend and effect of these imperfections an experimental and numerical study has been conducted. Some of the experimental findings are given in this paper as well as an example for the effect of geometric deviations on the structural behaviour under compressive loading. The simulations revealed that particularly the cell wall waviness has an impact on the stiffness and the failure load of honeycomb cores.

1. Introduction

Sandwich is widely used as a lightweight design solution for load-carrying components of aircraft due to their excellent mechanical properties such as high strength-to-weight and stiffness-to-weight ratios. Particularly, sandwich made of carbon fibre reinforced plastics (CFRP) face sheets and non-metallic honeycomb cores [1] is applied. Owing to the rather weak core material, this kind of structure is prone to a range of damages as a result of impact loading which may accidentally occur during 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. Therefore, it is necessary to determine damage size and severity in sandwich structures resulting from impact events and to predict the residual strength of the damaged components during the development process. Currently, this task is mainly performed by extensive testing: drop tests are carried out to simulate the impact loading, the damage size is determined by NDT methods and compression or shear after impact tests (CAI, SAI) provide the residual load carrying capability. These experimental procedures are rather costly and time consuming. Therefore, much research has been done to develop reliable simulation procedures based on finite element methods, which are able to predict the damage tolerance behaviour.

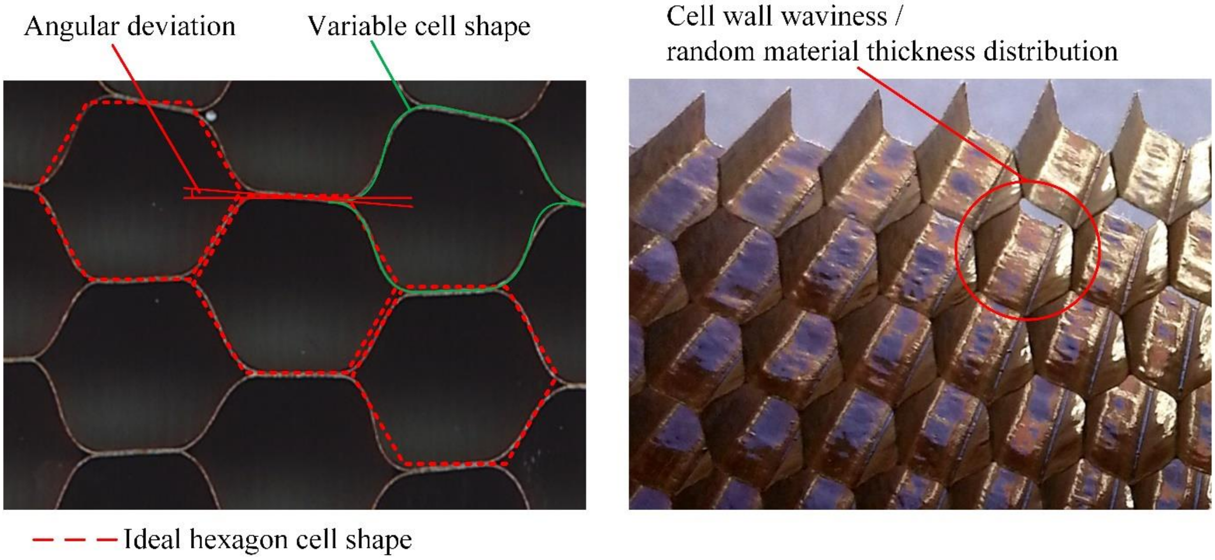
As long as only the global behaviour of sandwich components is investigated by finite element methods, it is sufficient to model the structure by using shell elements for the skins and solid elements for the core [2]. Such models permit only a macro-mechanical description of the core behaviour [3]. Thus, it is not possible to account for local failure modes in case of honeycomb cores. Nevertheless, these local effects are important when the damage tolerance behaviour is of interest. For this kind of problem more detailed numerical models [4-6] as well as a thorough knowledge about the imperfections existing in real honeycomb cores are required [7].

Excerpt from ISBN 978-3-00-053387-7

In this paper an experimental and numerical study is presented in which the influence of honeycomb core imperfections on the structural behaviour was investigated. Several types of imperfections such as resin distribution, cell wall waviness and geometrical shape deviation have been examined experimentally. Furthermore, their effect has been evaluated in a parametric study carried out by numerical simulation.

2. Analysis of real honeycomb structures

In the first phase of the research an extensive test campaign on honeycomb core material was carried out to characterise deviations from the ideal hexagonal cell geometry (Figure 1). This experimental program included the measuring of the angle variation of the parallel cell walls (Figure 1a) as well as the wall waviness (Figure 1 b). Additionally, the wall thickness distribution was determined. The test specimens consisted of Nomex® honeycombs with cell widths of 3.2 mm and 4.8 mm and densities of 48 kg/m³ and 32 kg/m³ respectively.



a) cell shape of honeycomb structure b) cell wall imperfections

Figure 1. Geometric imperfections of real honeycomb cores

2.1 Cell shape deviation

Deviations from the ideal hexagon shape are the result of the manufacturing method. The process generally applied to produce Nomex® honeycomb cores consists of following stages: In the first stage adhesive strips are printed on each layer of aramid paper, which are then stacked on top of each other and bonded under increased temperature and pressure [8]. When the adhesive strips are cured an expansion process results in the final shape of the honeycomb core (Figure 2). During this expansion the joined cell wall sections take an oblique position due to the placement tolerances of the adhesive strips on the paper. As shown in Figure 2 the connecting lines between the midpoints of the joined cell walls have a regular pattern of angular deviation. The wall orientations of the honeycomb samples investigated were determined by means of microsection. Angle variations up to 6° relative to the horizontal line were observed.

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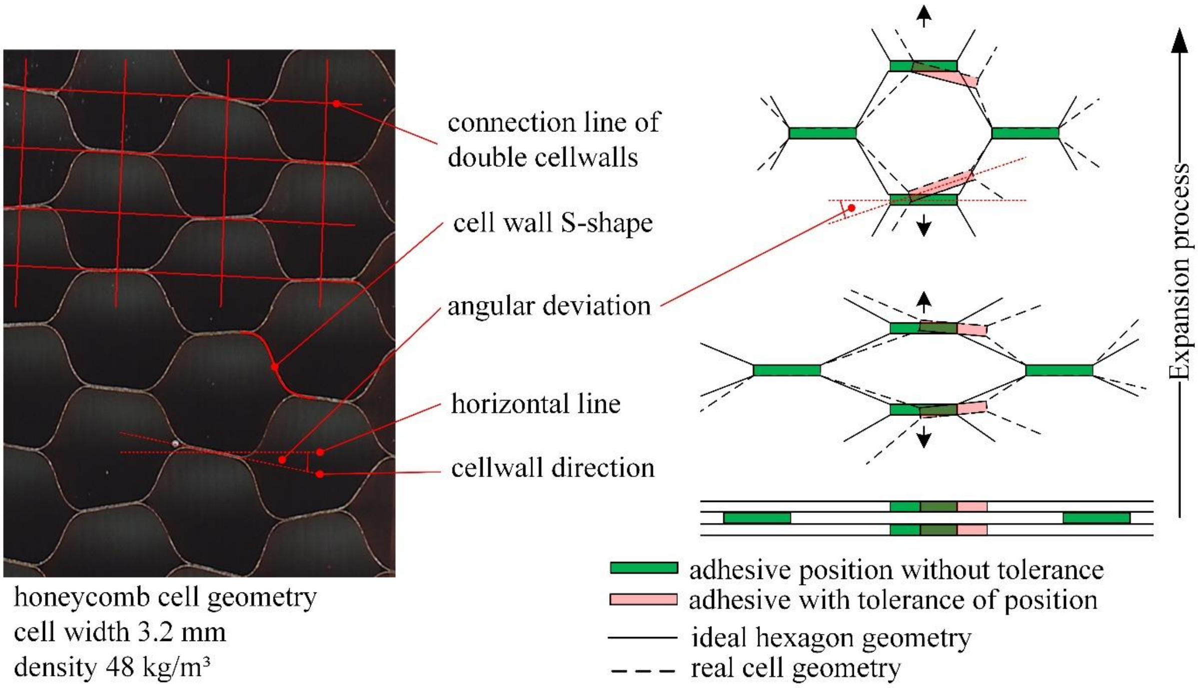

Figure 2. Angular deviation of honeycomb cores and schematic representation of the expansion process

Another result of the expansion process is the S-shaped form of the walls (see Figure 3). This is due to the bending stiffness of the aramid paper material. In the following manufacturing step, the honeycomb structure is immerged in a resin bath in order to impregnate the aramid paper. This procedure results in local resin concentrations at the corners as well as in the concave areas of the cells (Figure 3). The size of the resin concentrations was also measured by microsection.

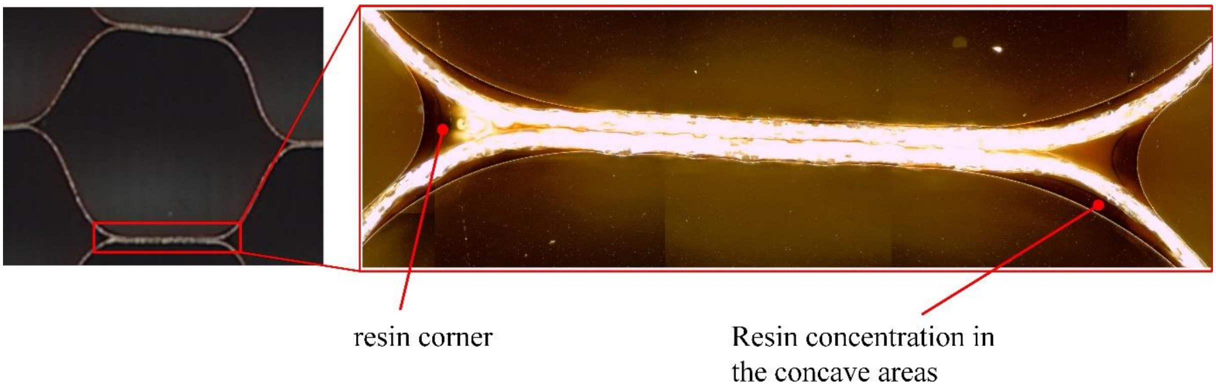

Figure 3. Resin distribution in a honeycomb cell

2.2 Cell wall imperfections

Two types of cell wall imperfections were investigated: the waviness and the thickness variation of the walls. For that purpose, two basic core configurations were considered: pristine honeycomb material in supplied condition and honeycomb as constituent of a manufactured sandwich.

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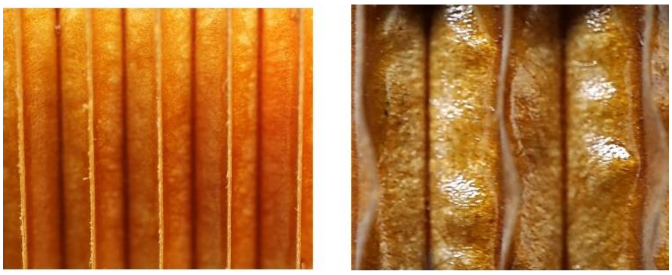
The main cause for wavy cell walls (see Figure 4) is the sandwich manufacturing process. The skin material is placed on the upper and lower face of the honeycomb core. Then skins and core are bonded under high temperature and pressure normal to the faces. The resulting compressive loads on the core can lead to a premature buckling of the cell walls.


a) honeycomb (supplied condition)

b) honeycomb (sandwich structure)

Figure 4. Comparison of cell wall waviness due to the manufacturing process

In a first approach both the three-dimensional measurement system GOM ATOS as well as a micro CT scanner were applied to visualise the waviness effect. Unfortunately, none of these methods proved to be suitable for a quantitative evaluation. Therefore, finally the microsection technique was employed to measure the amplitudes of the wavy cell walls. Typical micrographs used for this analysis are shown in Figure 5. The amplitudes of each cell wall were measured relative to its centerline, which is the straight line connecting the wall endpoints as shown in Figure 5.

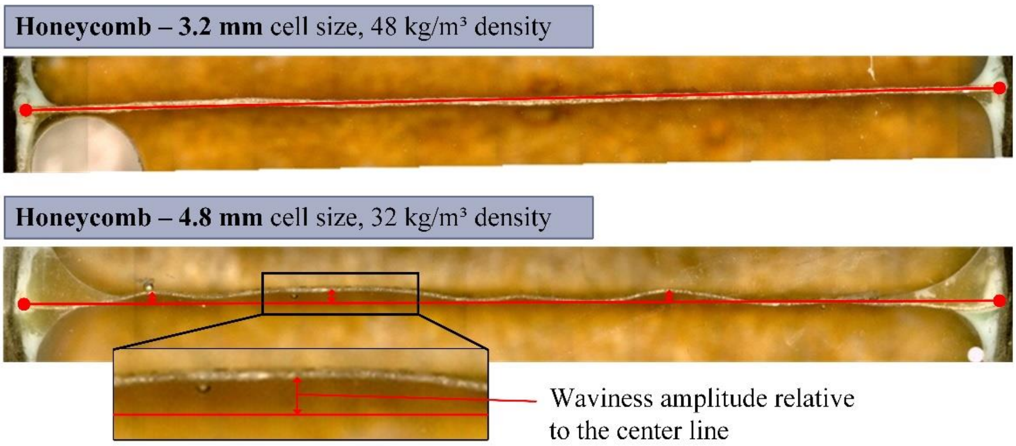


Figure 5. Analysis of the wall waviness of a honeycomb by microsection

A summary of the results is given in Table 1. For honeycomb types the range of measured amplitudes of the wall waves a_{wave} are given normalized with respect to the nominal wall thickness t_{HC} of the cells:

$$r_{Wave} = \frac{a_{Wave}}{t_{HC}} \tag{1}$$

As expected the amplitudes increase with the cell width. Also the manufacturing process contributes to this effect.

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Table 1. Waviness amplitudes r_{wave} of cell walls normalized to the nominal wall thickness

		HC 3.2-48	***HC 4.8-32***
Single cell wall	Honeycomb (supplied condition)	1.0 – 1.1	1.2 – 1.4
	Honeycomb (sandwich structure)	1.1 – 2.0	2.0 – 2.5
Double cell well	Honeycomb (supplied condition)	0.3 – 0.5	0.4 – 0.5
	Honeycomb (sandwich structure)	0.7 – 0.8	1.8 – 2.0

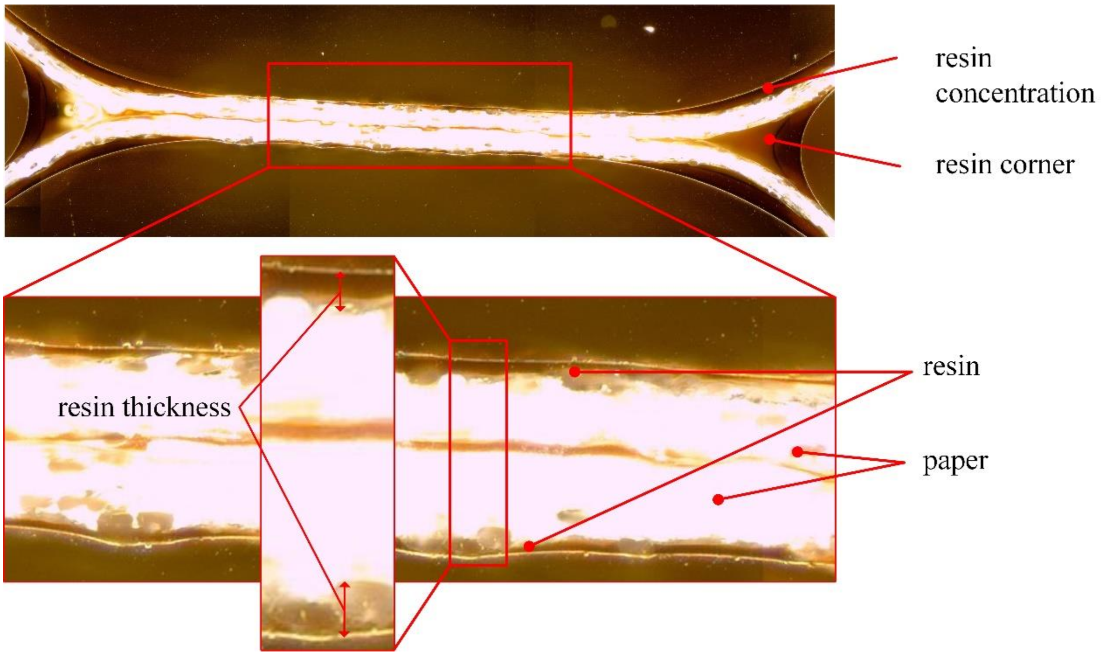

Figure 6. Investigation of the random material thickness distribution by using microsection

The microsection technique was also employed to determine the resin thickness distribution on single and double cell walls. A typical micrograph used for this purpose is shown in Figure 6. The results are summarized in Table 2, where the normalized resin thickness r_{Resin} is given:

$$r_{Resin} = \frac{t_{Resin}}{t_{HC}} \tag{2}$$

Table 2. Normalized resin thickness r_{Resin} on cell walls

	HC 3.2-48	***HC 3.2-64***	***HC 4.8-32***
Single cell wall	0.07 – 0.09	0.11 – 0.14	0.13 – 0.16
Double cell well	0.09 – 0.11	0.14 – 0.21	0.10 – 0.13

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3. Numerical modelling

In the second phase of the research numerical simulations were conducted to investigate the effect of the honeycomb core imperfections on the structural behaviour of sandwich structures. In order to provide finite element models of imperfect honeycomb sandwich structures, a parametric tool called SandMesh has been developed at the Institute of Aerospace Engineering. This program permits to generate very fast finite element models of sandwich structures with honeycomb, foam and folded cores. For the present study this tool was extended by the capability to model the following types of imperfections shown in Figure 7: cell wall waviness, angular deviation of the glued cell walls, resin concentrations and random material distribution.

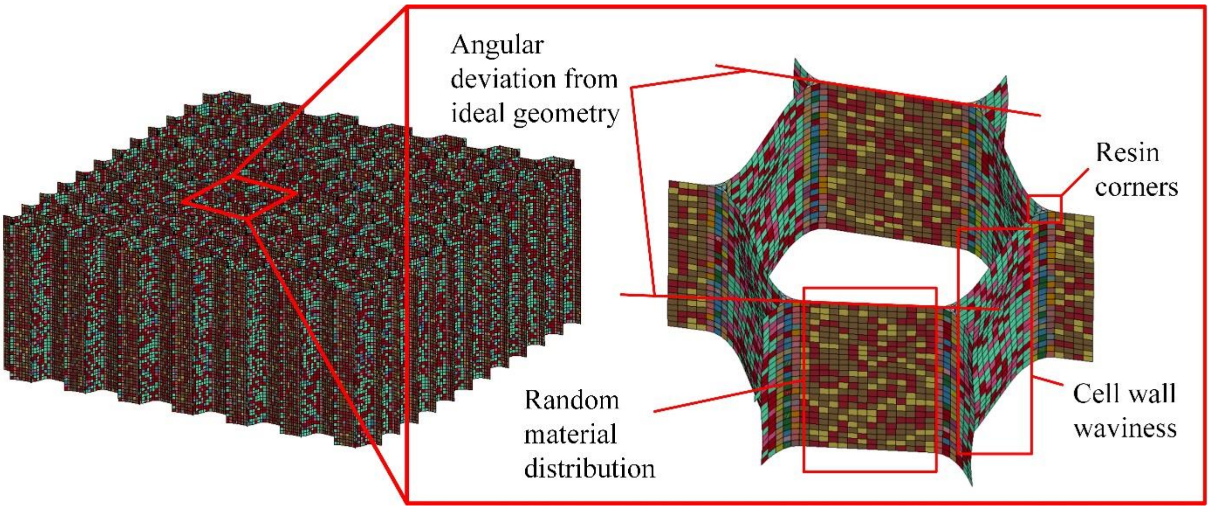

Figure 7. Implemented features of SandMesh for modelling honeycomb imperfections

In this study the honeycomb cell walls were modelled by 4-node shells and the resin corners by volume elements. The shell elements had three material layers in order to account for the distribution of paper and resin material in the walls.

4. Results of numerical investigations

Extensive parametric analyses were carried out employing the nonlinear dynamic solver LS-Dyna. The aim was to evaluate the influence of the experimentally determined imperfections on the structural behaviour. As an example a honeycomb core under compressive load normal to the surface is considered in the following. This case is particularly relevant for impact loaded sandwich structures.

The finite element model used is shown in Figure 8. The simulated core is made of a 15 mm thick honeycomb with a 3.2 mm cell width and a density of 48 kg/m³. The local cell geometry is based on data determined in the experimental study. The S-shape of the cell walls as well as the size of the resin corners were kept constant in each simulation. The material properties for the aramid paper as well as for the resin were taken from [9]. The compressive load was simulated by prescribed deformations on the upper side of the honeycomb block. The boundary conditions as well as a typical deformation pattern of the loaded honeycomb are also given in Figure 8.

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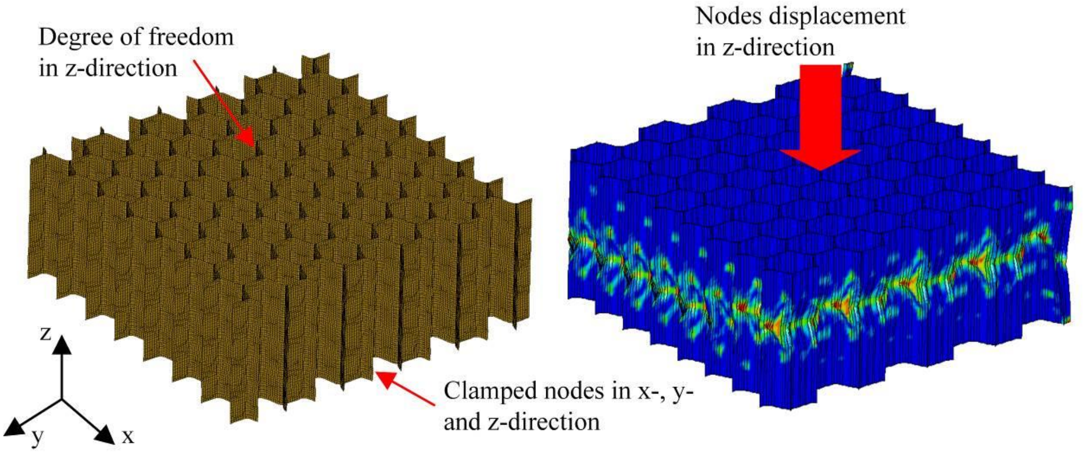
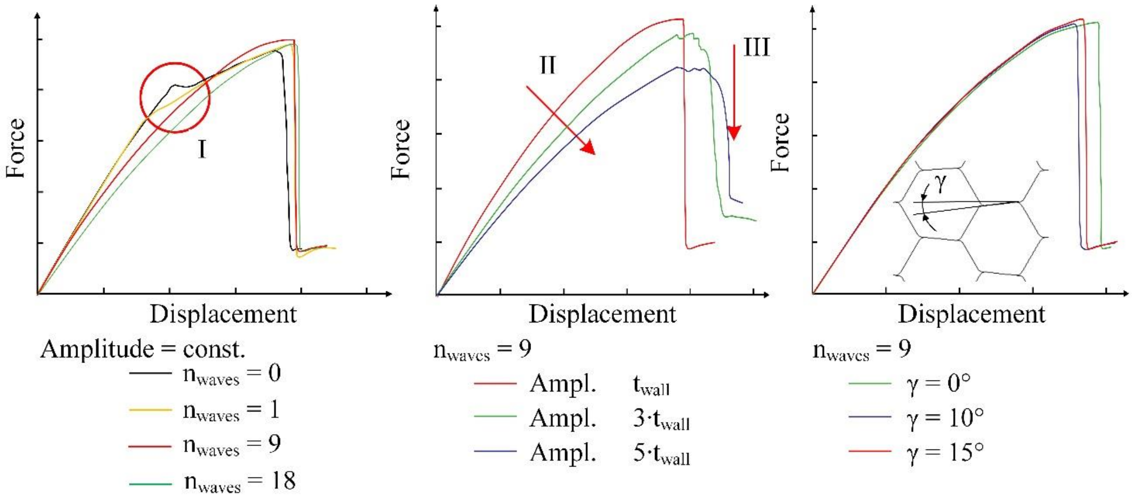


a) Simulation model

b) x-y-displacement caused by compression force

Figure 8. Boundary conditions and results of the simulation example

Some results obtained for this example are presented in Figure 9. The core displacements in the thickness direction are given as function of the compressive load for 3 different types of imperfections. For each type the effect of severity has been evaluated.



a) Variation of number of half-waves

b) Variation of wave amplitude

c) Variation of angular deviation

Figure 9. Simulation results of a honeycomb core under compression

The effect of waviness severity was investigated in the first step by varying the number of waves on the walls (Figure 9a). For flat cell walls the sandwich block shows a typical linear deformation behaviour up to the buckling load. In the post-buckling regime, a considerable decrease in stiffness can be observed. With an increasing number of waves the behaviour becomes nonlinear from the beginning, because the wall waves have the effect of a pre-buckling deformation. In the second step the amplitudes were analysed (Figure 9b). The force-deformation curves obtained clearly show a considerable effect on the core stiffness (II) as well as the core strength (III). Both decline with increasing amplitudes. In contrast, the angular deviations of the cell walls joined by the adhesive strips show no significant influence on the structural behaviour (Figure 9c).

5. Conclusions

The experimental study performed in the presented research project provided a comprehensive data base on typical imperfections observed in honeycomb cores. Particularly, the knowledge gained on the quantitative magnitude is useful for including imperfections in detailed numerical models for foreign object impact simulations. This contributes to further improve the accuracy of the damage size and severity prediction.

For the numerical investigations a parametric model generator was developed which permits to create finite element models of honeycomb cores including the relevant imperfections. Within the scope of the parametric simulation study, the effect of imperfections on the structural behaviour was evaluated. For the example of a compressive loaded honeycomb it was shown that particularly the waviness of the cell walls can impair the strength and stiffness of the core.

Acknowledgments

This research was performed within the LuFo V-1 project SCHACH funded by the German Federal Ministry for Economic Affairs and Energy. The simulations were run on the Bull HPC-Cluster of the Center for Information Services and High Performance Computing (ZIH) of TU Dresden. Both the financial support as well as the computing capacity provided is gratefully acknowledged.

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Excerpt from ISBN 978-3-00-053387-7