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# Analysis of structural performance of sandwich plates with foam-filled aluminum hexagonal honeycomb core

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ABSTRACT

Exploitation experience of honeycomb sandwich structures has shown that one of the most frequently encountered in-service problems is debonding at the interface between face sheets (skins) and core. Filling of honeycomb type cores with foam allows to enhance the damage resistance to the debonding propagation, but on the other hand it changes the structural responses of sandwich structure. The aim of the paper is to estimate of a polymeric foam influence on the free vibration and buckling characteristics of sandwich plates with a hexagonal honeycomb core. The analyses of sandwich plates with hollow and foam-filled honeycomb cores are carried out using the commercially available finite element code ABAQUS. The sandwich plates were modelled on the basis of simplified three-layered continuum models. The displacement-based homogeneous technique using finite element method (FEM) is applied to evaluate the effective elastic properties of core for both hollow and filled with foam honeycomb cores. The comparative results of load carrying capacities and magnitudes of natural frequencies of the sandwich plates are presented. The structural benefits of foam-filled sandwich plates are briefly discussed.


## 1. Introduction

In recent years, structures of a sandwich are widespread in the modern industry. High stiffness and strength at the given minimum weight make sandwich panels attractive for using as components of modern aircrafts, aerospace vehicles, boats, building constructions and other applications where weight saving is critical [1]. This structural benefit of the sandwich structures is due to the fact that a lightweight core separates two thin, stiff and strong face sheets. This separation increases the structure resistance to bending and buckling loads. However, the core must provide the structure stiffness in the transverse direction in order to prevent the sliding of face sheets over each other.

A big number of core materials and core configurations have been proposed nowadays. The most commonly used core materials are honeycomb and foams [2]. The foam cores are preferably used when the waterproof, sound and heat insulation qualities of cores are required. Additionally, the foam cores are the least expensive among core materials and can offer some advantages in sandwich manufacture. The honeycomb cores possess a higher stiffness-to-weight ratio compared to foam core materials. However, the weakest point of such core is the small adhesive area of honeycomb cells with face sheets that due to manufacturing defects or in-service conditions and mechanical loading can induce debonding between them. The filling of honeycomb cells with foam can be considered as the enhancement of debonding resistance and ability to produce new types of sandwich cores [3]. This concept combines the benefits of honeycomb and foam cores. The increased adhesive area of foam-filled honeycomb cells is only one of them. On the other hand, the filling leads to changes of the dynamic properties of the honeycomb sandwiches.

The aim of this study is to appreciate the effect of the foam-filled hexagonal honeycomb core onto characteristics of free vibration and stability responses of the sandwich plates. The analyses of the foam-filled honeycomb sandwich plates will be carried out using a simplified three-layered continuum model. The equivalent material properties such as effective elastic moduli for homogeneous core will be obtained by deformation-based homogenization technique using FEM.

## 2. Modelling

The finite element modelling of honeycomb sandwich panels can be performed on the basis of the detailed three-dimensional (3D) and simplified approaches [4]. It is obviously, the computational efforts associated with detailed models increase very rapidly as the number of cells in the panel core increase. For reasons of

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numerical efficiency, the modelling of the sandwich panels is usually carried out by assuming several simplifications. Such approach implies that the 3D high heterogeneous honeycomb sandwich structure is replaced with the equivalent three-layered continuum, where each layer (two face sheets and core) is modelled as a homogeneous and an anisotropic material with effective properties. Thereby, the cellular honeycomb core has to be treated as a quasi-homogeneous "effective" layer. This will give the possibility to apply shell or solid elements to model the honeycomb sandwich panels. By doing that, the total number of unknowns of the finite element model will be reduced considerably, and consequently, the simulation time will come down to an affordable range. However, the reliability of the model is critically dependent on the prediction accuracy of effective elastic constants of the core. The calculations of the latter unlike the face sheet properties, which can even be laminated plate, are more complicated. Besides, the three-layer arrangement leads to the use of the various sandwich theories characterized by the wide range of assumptions concerning the through-thickness behavior. A lot of research has been devoted to this problem. A detailed review on the computational modelling of sandwich plates and shells can be found in [5]. The validity of similar models of the sandwich panels in comparison to detailed 3D ones have been found to be quite adequate for analyses which do not require to examine any local effects [6]. Consequently, the predictions of the global response quantities such as free vibration frequencies and critical loads of the sandwich plates with foam-filled honeycomb core can be done based on the equivalent continuum models. Assuming that the material properties of the face sheets are known, the main attention in this paper is focused on the modelling of effective properties of the core material.

### 2.1. General concepts

The effective elastic properties of the hexagonal honeycomb core for both hollow and filled with foam cases can be evaluated on the basis of a homogenization concept for periodic structures [7]. Within this technique, the smallest representative part of the periodic structure, referred to as a unit cell, is introduced. It is assumed that the whole structure can be reproduced from the unit cell by means of appropriate mirror images and periodic repetition. Then, the homogenization of the cellular microstructure can be performed. The unit cell should be analyzed under influence of selected load cases, and the properties of the associated quasi-homogeneous "effective" continuum are determined in such a way that the stress–strain responses between the initial cellular and homogenized "effective" structures are equivalent at the macroscopic level. Finally, according to homogeneity assumption, periodic elastic moduli of the studied periodic structure are replaced by effective constant elastic moduli.

In order to obtain the macroscopic elastic moduli of the foam-filled hexagonal honeycomb core, the 3D finite element model for the unit cell is considered. The finite element approaches have been used earlier to predict the effective out-of-plane and in-plane stiffness properties of the hollow honeycomb core are described in [8] and [9], respectively. Here, these FE techniques are adapted for filled with foam honeycomb core. The homogenization analyses were done with ABAQUS software [10] and have been performed under the following assumptions:

- The hexagonal cell itself is assumed to be perfectly regular with edge of the length $l$ (Fig. 1c).
- The material behavior is linear-elastically and the difference in compressive and tensile responses of the polyvinyl chloride (PVC) foams is not taken into account.
- The perfect bonding between both core-to-face sheets and wall-to-wall contacts as well as at the interface of the cell wall and the cell filler (foil-to-foam).
- Buckling under compression of cell walls is disregarded.
- Face sheets are stiff enough so that their in-plane deformation is not disturbed by distortion of the core cell structure.

### 2.2. Core out-of-plane properties

Fig. 1 shows geometry of the hexagonal honeycomb sandwich core and the unit cell geometrical parameters. Due to symmetry of the unit cell structure only one-quarter of its in-plane size and half its height can be considered, Figs. 2 and 3. For calculation of effective elasticity constants of the considered honeycomb core material in the transverse direction the deformed shape of the honeycomb cell walls under pure shear stresses and transverse compression stress should be considered. The homogeneous stress fields were introduced to the cell by imposing the corresponding uniform displacement fields. The shear stress fields in the cell walls were simulated by a rotation of the top and bottom faces of the honeycomb unit cell with respect to the $x$- and $y$-axes, whereas the compression was introduced by the displacement of the faces along the $z$-axis, Figs. 2 and 3.

Each wall of the unit cell was modelled using shell element S8R5 with five degrees of freedom (DOF) per node. Mesh-sensitiv-

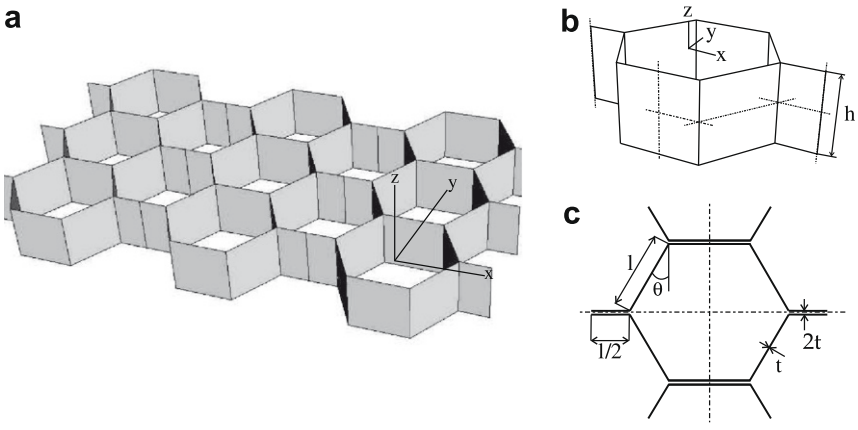


**Fig. 1.** Honeycomb core structure: (a) general view, (b) honeycomb unit cell, and (c) unit cell parameters.

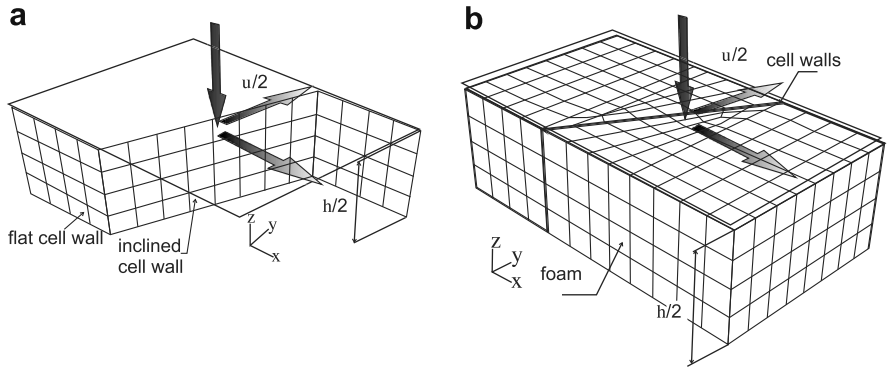


**Fig. 2.** One-quarter of the unit cell FE model: (a) the hollow unit cell and (b) the foam-filled unit cell.

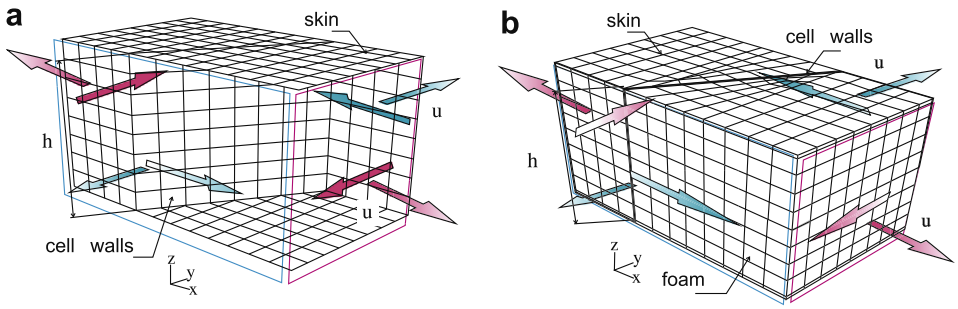


**Fig. 3.** One-quarter of the unit cell FE model including face sheets: (a) the hollow unit cell and (b) the foam-filled unit cell.

ity analyses were previously carried out for studied FE model, thereby the chosen mesh will be not discussed further. These studies showed that the $4 \times 4$ mesh for flat cell walls and the $8 \times 4$ mesh for inclined cell wall were optimum for the homogenization analyses. The foam material was modelled by the solid elements C3D20R with three displacements per node. The coupling between different elements in the mesh was achieved by the constraint of the redundant DOFs where these elements have contacted. The size of each solid element was set of conditions of the compatibility with shell elements and so that their form was close to cubic. Appropriate boundary conditions were imposed to provide straightness and verticality of the flat cell walls. For calculation of $G_{xz}, G_{yz}$ and $E_z$ the top face of the unit cell was subjected to a uniform displacement $u/2$ along $x$-, $y$- or $z$-directions, respectively, while the bottom face of the unit cell remains fixed. Then, the reaction forces in each node on the constrained edge are added up to give the total reaction force applied on a hexagonal block of the equivalent homogeneous material. Then, the corresponding stress was calculated by dividing the total force by the area of this equivalent block. The strain was found by dividing the applied displacement by the initial height of the unit cell. Thereby, Young's and shear moduli were calculated from the Hooke's law, where the equivalent stresses are divided by the equivalent strain.

**Table 1**
Elastic properties of polyvinyl chloride (PVC) foams

| | $E$ (GPa) | $\rho$ (kg m$^{-3}$) | $\nu$ |
|---|---|---|---|
| PVC H60 | 0.056 | 60 | 0.27 |
| PVC H100 | 0.105 | 100 | 0.32 |
| PVC H200 | 0.230 | 130 | 0.32 |

In the numerical examples the following material properties were taken into account. The honeycomb foil material was described by: $E = 72$ GPa, $\rho = 2770$ kg m$^{-3}$, $\nu = 0.31$ (the similar data like in [8]). The properties of polyvinyl chloride foam fillers of different densities are specified in Table 1, [11]. The unit cell dimensions were equal to: $l = 1$ mm, $t = 0.08$ mm, $\theta = 30°$, $h$ was varied between 1 and 10 mm as in the figure. The analytical predictions

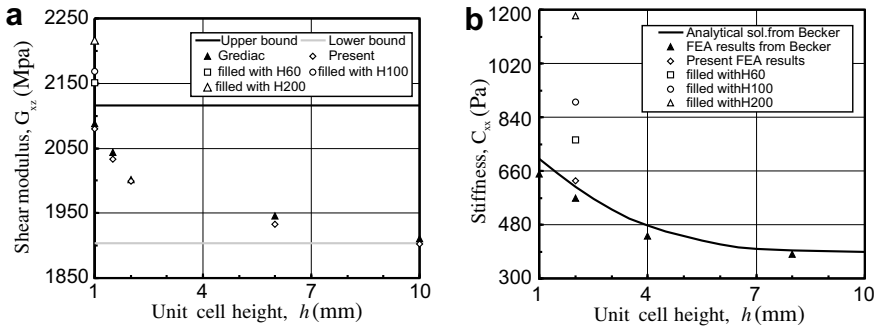


**Fig. 4.** Elastic constants vs. unit cell height: (a) shear modulus and (b) stiffness in $x$-direction.

based on the Gibson and Ashby formulae [12], numerical calculation obtained with ABAQUS and given in [8] concerning estimation of the shear modulus $G_{xz}$ for hollow and for filled honeycomb cores with thickness, $h$ equal to 1 mm are shown in Fig. 4a. The pointed out methods give the similar results. It should be noted, that foam-filling increases transverse properties of the honeycomb core and their magnitudes are greater when the foam density increases.

### 2.3. Core in-plane properties

Although, from the structural performance point of view the out-of-plane elastic components of the honeycomb core are most important, for purposes of generality, the in-plane $E_x, E_y$ and $G_{xy}$ moduli were calculated too. FE models of the unit cell for calculation of the in-plane constants for both with and without the foam in honeycomb are shown in Fig. 3a and b, where the face sheets also included.

The mesh was comprised of elements mentioned above, but their amount in the thickness direction was two times greater than for the calculation of out-of-plane constants. The face sheets were meshed by the same shell elements as cell walls. Uniaxial tension loading and shearing were simulated by imposing a uniform displacement on the face sheets of the unit cell in $x$- or $y$-directions and along $x$- or $y$-directions, respectively (Fig. 3). Then, the stiffness $(C_{xx}, C_{yy}, C_{xy})$ can be obtained using the following relationship: $C = 2U/(\epsilon_{eq}^2 V)$, where $U$ is the total cell strain energy, $\epsilon_{eq}$ is the equivalent homogeneous strain that correspond to displacement field and $V$ denotes the volume of the hexagonal block equivalent to the unit cell. Knowing the stiffnesses, according to the well-known relationships, it is possible to evaluate the in-plane shear and Young's moduli, respectively. The foil material and dimensions of the unit cell taken into calculations were the same as in [9]: $E = 72.2$ GPa, $\nu = 0.34$, $l = 4$ mm, $t = 0.05$ mm, $\theta = 30°$, $h = 2$ mm. The calculated effective stiffness $C_{xx}$ for both hollow and foam-filled cases compared with data presented in [9] is shown in Fig. 4b.

It may notice that the filling with foam of the honeycomb core increases its initial in-plane stiffness $C_{xx}$ and the longitudinal core stiffness rises almost twice for H200 foam filler as shown in Fig. 4b.

## 3. FE analyses of honeycomb sandwich plates

Two different problems that focus on the effect of differences in honeycomb material properties, related to the foam filler presence, on static and dynamic response of honeycomb sandwich plates are considered. The first problem is a free vibration analysis of the sandwich plates and the second one is a buckling analysis. The commercial FE software ABAQUS™ v. 6.5 was used for modelling. The suitable mesh for each FE model of the sandwich plates was preliminary established by the comparison between results (natural frequencies or critical loads) calculated for initial and finer meshes, then the optimum mesh is provided by insignificant differences in them.

### 3.1. Free vibration analysis

The effects of property differences in the honeycomb core on the eigenfrequencies of the sandwich plates are examined by the comparison between finite element predictions hollow core and filled with foam one. Free vibration analysis of the honeycomb sandwich plates was performed in the example for which experimental and numerical data are available [13]. The rectangular sandwich plate $a \times b = 180 \times 135$ mm, with core thickness $h_c = 5$ mm and total thickness $h = 7.5$ mm had perfectly free all edges. The constituent materials used for the sandwich plates consist of carbon fiber reinforced plastic (CFRP) and hollow or filled with PVC foam (Ff) honeycomb cores. The hexagonal honeycomb core are made of aluminium foil (5052 aluminium alloy: $E = 70$ GPa, $\nu = 0.3, \rho = 2680$ kg m$^{-3}$) of thickness $t = 0.0254$ mm and the cell wall size $l = 1.833$ mm. The given and calculated properties of these materials are listed in Table 2. Here the densities of foam-filled honeycomb cores were obtained on the basis of rule of mixtures.

The first torsional and bending modes predicted by ABAQUS with a $10 \times 8 \times 4$ mesh of the continuum shell element SC8R and given in [13] are presented in Table 3 and in Fig. 5a and b. The results are found to be close to the Tanimoto's data. However, some overestimation of the frequencies calculated with ABAQUS within 8–10% takes place. This shows that SC8R elements, used for the sake of keeping the CPU time during calculations, is not enough accurate. Hence, in order to predict the frequencies of sandwich plates with greater accuracy the application of FE models using solid elements can be more preferable.

### 3.2. Buckling analysis

The next problem illustrates the influence of the foam-filling on the load capacity of sandwich plates. A square honeycomb sandwich plate $a = b = 225$ mm$^2$ simply supported on all four edges and compressed in one direction by uniform edge load, $q$ was considered. The thicknesses of the face sheets and honeycomb core and the material properties of the core are the same

**Table 3**
Natural frequencies (Hz) of perfectly free sandwich plates

| Mode type | Experiment | Tanimoto et al. | Present | | | |
|---|---|---|---|---|---|---|
| | | | AlH | FfH60 | FfH100 | FfH200 |
| Torsional | 603.4 | 627.7 | 655.2 | 639.2 | 625.4 | 617.6 |
| Bending | 1212.8 | 1230.9 | 1329.7 | 1319.2 | 1303.9 | 1298.6 |

**Table 4**
Critical load (N/mm) of simply supported sandwich plates.

| Buckling load | AlH | FfH60 | FfH100 | FfH200 |
|---|---|---|---|---|
| $q$ (N/mm) | 665.58 | 670.61 | 676.15 | 688.72 |

**Table 2**
Mechanical properties of materials constituting sandwich plates

| | $E_x$ (MPa) | $E_y$ (MPa) | $E_z$ (MPa) | $G_{xy}$ (MPa) | $G_{xz}$ (MPa) | $G_{yz}$ (MPa) | $\nu_{xy}$ | $\rho$ (kg m$^{-3}$) |
|---|---|---|---|---|---|---|---|---|
| CFRP | 140e3 | 10e3 | 10e3 | 3800 | 4600 | 4600 | 0.25 | 1650 |
| *AlH* | | | | | | | | |
| [12] | 0.430 | 0.430 | 1493 | 0.108 | 341.1 | 205.4 | 0.495 | 57.17 |
| Present | 0.461 | 0.461 | 1494 | 0.194 | 341.7 | 192.1 | 0.423 | 57.17 |
| FfH60 | 0.672 | 0.672 | 1549 | 0.238 | 356.2 | 212.1 | 0.408 | 101.95 |
| FfH100 | 0.788 | 0.788 | 1598 | 0.282 | 374.3 | 224.4 | 0.393 | 141.31 |
| FfH200 | 1.061 | 1.061 | 1722 | 0.386 | 422.1 | 238.9 | 0.374 | 170.83 |

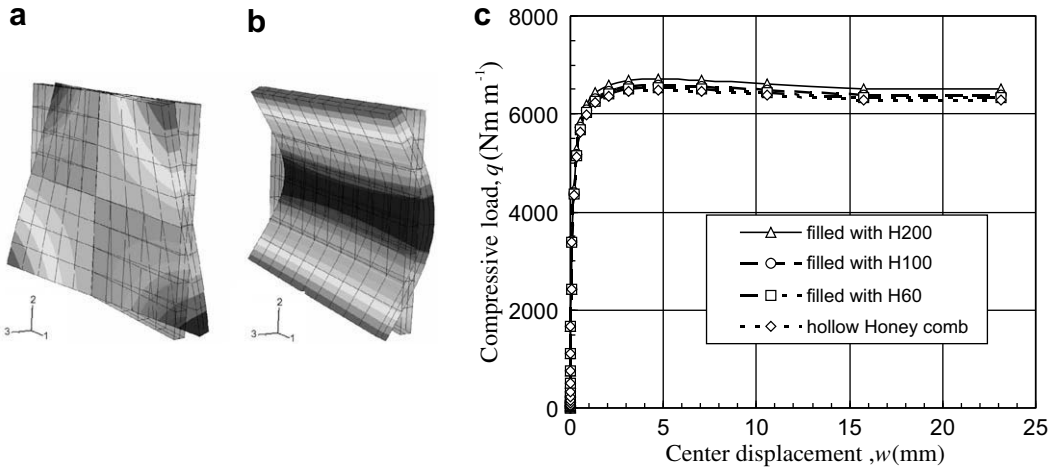


**Fig. 5.** Results FE analyses: (a) torsional mode, (b) bending mode, and (c) load–displacement curves.

as the above mentioned case of the sandwich plate but its face sheets were made of the aluminum material such as the foil material of the core. Because of the symmetry in geometry, loading and material properties, only one-quarter of the sandwich plate can be adequate to model. The lowest buckling loads calculated by ABAQUS with a $10 \times 10$ mesh of the shell element S4 are summarized in Table 4.

In order to investigate the influence of the filling effect on the load–displacement responses of the sandwich plates, the non-linear postbuckling analysis is performed. The necessary perturbation of the solution was provided by initial geometry imperfection of the sandwich plate, which corresponded to the first buckling mode with imperfection magnitude taken as 1% of the total plate thickness. The edge buckling load is applied by requesting that the load will be increased monotonically up to the moment when the center displacement of the plate is greater than its double total thickness. The load–displacement analysis curves are shown in Fig. 5c.

## 4. Conclusions

The numerical investigations presented in the paper lead to the following conclusions:

(i) Global responses such as mode shapes corresponding to the free vibration and linear buckling as well as view of the load–displacement curves under non-linear buckling of sandwich plates with aluminum hexagonal honeycomb core filled with foam are qualitatively similar to hollow one.

(ii) Introduction of the foam in the honeycomb core causes moderate reduction of the magnitudes of the natural frequencies. This effect is magnified by the density of foam fillers, which insignificantly increases also the stiffness and total mass of the filled sandwich plates.

(iii) Filling of the honeycomb with the foam promotes the slight increases of buckling loads and the insignificant decreases of imperfection sensitivity of foam-filled sandwich plates.

On the other hand, adding the foam can induce changes in stress distributions in the core-to-sheet faces interface. The influence of the foam filler on the local effects in the filled honeycomb core will be investigated in the next paper.

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