Deformation Behavior of 2D Composite Cellular Lattices of Ceramic Building Blocks and Epoxy Resin

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2D lattice structures with ordered cell designs based on honeycombs are built from modular composites of ceramic building blocks and epoxy resin. The variation of structural parameters as slenderness $t_2 g^{-1}$ and piezoelectric active area $q$ changes the cell design. Finite element method (FEM) simulations based on algorithm-generated models within a structural parameter range determine the effect of thermal expansion of different materials ($\alpha_{\text{material}}$) on the mechanical behavior in plane strain mode representative of piezoelectric excitation. The stress distribution $\sigma_{yy}$ and strain amplification $a_\theta$ as a function of deformation are analyzed for $\text{Al}_2\text{O}_3$-PZT and PZT-PZT building block composites. The aim herein is to increase $a_\theta$ by modifying structure design. Furthermore, zero deformation with simultaneously occurring stresses is investigated.

1. Introduction

The ordered and periodical cell design leads to highly anisotropic mechanical properties in 2D cellular solids. The cell design is divided into the spatial configuration of voids and solids, cell size, and cell orientation, leading to a certain geometric and relative density. Slight structural changes cause large effects on the strength and stiffness of the complex macroscopic structure. Strength and stiffness are proportional to the solid volume fraction of the material.

In general, lattices deform above a critical strain by bending or stretching, and finally the cells collapse. Regular honeycombs show a linear elastic deformation behavior under in-plane compression stress. Depending on the mechanical properties (strength, Young’s modulus, flexibility) of the used material, cellular solids fail by elastic buckling, plastic yielding, creep, or brittle fracture. The cell collapse ends by touching the opposite cell walls. Compression stress causes the walls to bend, which limits the strength of the cellular solids. However, during compression, the struts of predominantly stretch-dominated structures support axial loads. This is interesting for weight-efficient structural applications as lightweight catalyst structures.

Algorithms can describe the geometry of the periodic cellular structures and therefore straightforwardly are used in finite element (FE) simulation methods to support the experimental setup. Geometric parameters such as slenderness $t_2 g^{-1}$ as a ratio of cell wall thickness $t_2$ and distance $g$, length $L_{\text{edges}}$, sample thickness $s$, and the angle between columns and levers $\theta$ can be varied.

The structure designs can be modified to achieve a high strain amplification $a_\theta$ (assuming a uniaxial loading in Y-direction).

In this work, 2D honeycomb-based cellular solids with a slenderness ratio $t_2 g^{-1}$ from 0.11 to 1.00 were generated based on an algorithm (see supplement data) by a python script. In contrast to the previous studies of cellular structures, the investigated structures were built up from individual segments, referred to in the following as building blocks ($\text{Al}_2\text{O}_3$, PZT). The blocks were connected by an epoxy adhesive layer of 0.1 mm thickness with negligible influence on mechanical properties. Thus, the cellular structure can be built from modular units, which can be excited (mechanical, thermal, electrical) individually.

The thermal expansion and the piezoelectric deformation are linked to the material crystal structure. So, it was assumed that thermal expansion $\epsilon_{\text{thermal}}$ correlates directly with the piezoelectric strain deformation $\epsilon_{\text{Piezo}}$. This makes it possible to simulate piezoelectric strain behavior (hereafter referred to as pseudopiezoelectric behavior, $E_3 \times d_3$) via the thermal expansion coefficient $\alpha$ in a simplified way, as shown in Equation (1).

$$\epsilon_{\text{Piezo}} = E_3 \times d_3 = \alpha \times \Delta T = \epsilon_{\text{thermal}}$$  \hspace{1cm} (1)

Piezoelectric active components were assigned a thermal expansion coefficient of $\alpha \neq 0 \text{K}^{-1}$ and passive components of $\alpha = 0 \text{K}^{-1}$.
2. Experimental Section

The software MarcMentat (Version 2015.0.0, MSC Software, Munich, Germany) with the possibility of nonlinear calculations was used for FE simulations. MarcMentat offers a limited direct python interface or an extensive software control by the so-called procedure files. These files were generated by python scripts (Version 3.5, Python Software Foundation, Beaverton, Oregon, USA). They were used to automate and manage the structure creation, material properties, meshing of modular units, and boundary conditions.

A schematic drawing of the designed modular structure and all parameters is shown in Figure 1. The modular structure contained three different parts: frame, lever, and column. The parameters $t_1$ (thickness of lever) and $g$ (distance lever column) were varied in the range of $0.75$–$1.50$ mm and $1.50$–$6.95$ mm and were combined in the slenderness ratio $t_2 \frac{g}{C_0}$, as shown in Table 1 and Figure 1. The other geometric parameters as cell wall thickness $t_1$, length $L_{ges}$, sample thickness $s$, and angle $\theta$ were kept constant to limit the variation number.

The material variations were limited to the following cases: 1) monolithic structure PZT, 2) modular Al₂O₃–PZT composites with Al₂O₃ frame, PZT levers, and PZT columns, and 3) modular PZT–PZT composites with frame, levers, and columns of PZT; for the assigned material properties, see Table 2.

Passive parts were assigned a thermal excitation of $\alpha = 0 \, K^{-1}$ and active parts $\alpha \neq 0 \, K^{-1}$. Depending on the types of excitations, the coefficient of thermal expansion could be positive (Expansion, $\alpha = +76 \times 10^{-6} \, K^{-1}$), negative (Shrinkage, $\alpha = -76 \times 10^{-6} \, K^{-1}$), or Neutral ($\alpha = 0 \, K^{-1}$), as shown in Figure 2. The different thermal expansion coefficients and the excitation of the three composites were combined to four excitation modes. The active area $q$ describes the amount of piezoelectric active material, in which the fraction of the structure was deformed by the piezoelectric excitation, as shown in Table 3.

In the modes (E|E|E) and (E|E|N), $\alpha$ was set positive for levers and columns but different for the frame: in (E|E|E), $\alpha$ was positive and in (E|E|N) $\alpha = 0$. There was no excitation of the frame in modes (E|S|N) and (S|E|N), whereas both modes had an opposite excitation of levers and columns.

Due to boundary conditions with no displacement ($Y = 0$ and $Y = L$), the deformation in the X-direction was almost zero and $\varepsilon_x$ as well as $\sigma_{xx}$ was neglected and focused on the Y-direction.

| Slenderness | $t_2$ | $g$ |
|------------|------|-----|
| $t_2 \frac{g}{C_0}$ | mm | mm |
| 1.00 | 1.50 | 1.50 |
| 0.48 | 1.25 | 2.59 |
| 0.26 | 1.00 | 3.82 |
| 0.14 | 0.75 | 5.16 |
| 0.11 | 0.75 | 6.95 |

Table 2. Assigned material properties for FE simulations.

| Material | Density $\rho$ [g cm$^{-3}$] | Young’s modulus $Y$ [GPa] | Poisson’s ratio $\nu$ | Thermal expansion coefficient $\alpha$ [K$^{-1}$] | Pseudo-piezoelectric simulation $\alpha$ |
|----------|---------------------------|----------------|-------------------|---------------------------------|-----------------------------------|
| PZT      | 7.85                      | 63 [39]       | 0.32 [39]         | 0.81 [27]                      | 76 [20]                          |
| Al₂O₃    | 3.96 [40]                 | 400 [40]      | 0.22 [40]         | 5.7 [21]                       | 0                                 |
| Epoxy    | 1.18 [40]                 | 4 [6]         | 0.35 [6]          | 76 [27]                        | 0                                 |

Figure 1. Modular lattice structure and its parameters. The color indicates the different parts: frame (white), lever (green), and column (blue). In addition, the five structures with different slenderness $t_2 \frac{g}{C_0}$. 

Table 1. Parameter $t_2$, $g$, and the slenderness $t_2 \frac{g}{C_0}$ for structures with constant $L_{ges} = 10$ mm, $t_1 = 1.5$ mm, $h = 2.7$ mm, $\beta = 34^{\circ}$, $\theta = 20^{\circ}$, and relative density $\rho_{relative} = 0.35 \pm 0.01$. 

Figure 1. Modular lattice structure and its parameters. The color indicates the different parts: frame (white), lever (green), and column (blue). In addition, the five structures with different slenderness $t_2 \frac{g}{C_0}$. 

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Figure 2. Stress distribution in $\sigma_{yy}$ under pseudopiezoelectric excitations modes: A) structure PZT with mode (E|E|E), B) Al$_2$O$_3$–PZT with mode (E|S|N), C) PZT–PZT with mode (E|S|N), D) Al$_2$O$_3$–PZT with mode (S|E|N), E) PZT–PZT with mode (S|E|N), F) Al$_2$O$_3$–PZT with mode (E|E|N), and G) PZT–PZT with mode (E|E|N).
Table 3. Excitation mode and their active areas $q$: expansion E, shrinkage S, and neutral N for the different excitations with corresponding $\alpha$.

| Excitation mode | $E$ | $E$ | $E$ | $E$ | $S$ | $N$ | $S$ | $E$ | $N$ | $E$ | $E$ | $N$ |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Lever           | $a = +, e$ | $a = +, e$ | $a = -, s$ | $a = +, e$ | $a = +, e$ | $a = +, e$ |
| Column          | $a = +, e$ | $a = -, s$ | $a = +, e$ | $a = +, e$ | $a = +, e$ | $a = +, e$ |
| Frame           | $a = +, e$ | $a = 0, n$ | $a = 0, n$ | $a = 0, n$ | $a = 0, n$ | $a = 0, n$ |
| Active area $q$ | 1.00 | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 |

Based on the unit cell deformation after displacement, calculation of the resulting strain $\varepsilon_y$ was carried out in the center of the sample to minimize interferences from the edges. The strain amplification $a_y$ (measured at height $Y = L/2$) was defined as a function of the simulated mechanical deformation divided by the theoretical thermal expansion of the bulk material ($\varepsilon_{\text{thermal}} = 0.11\%$), the relative density, and the active area $q$.

### 3. Results

#### 3.1. Stress Distribution Under Different Excitation Modes

The stress distribution $\sigma_y$ changed with the excitation mode and Young’s modulus, as shown in Figure 2, and therefore with the slenderness ratio $t_2$ $g^{-1}$. The assigned Y-displacement of $Al_2O_3$–PZT and PZT–PZT building block composites led to a similar stress distribution $\sigma_y$ inside the samples. This stress increased with increasing Young’s modulus.

The mode (E|E|E) showed a minimum of $\sigma_{y E} = +22$ MPa at $t_2$ $g^{-1} = 1.00$ and a maximum of $-92$ MPa at $t_2$ $g^{-1} = 0.11$, respectively. For $t_2$ $g^{-1} < 0.26$ and $t_2$ $g^{-1} > 0.14$ stress, $\sigma_y$ decreased within the lever to a minimum value of $-59$ MPa at $t_2$ $g^{-1} = 0.48$, as shown in Figure 2A. A homogeneous stress distribution $\sigma_y$ was determined for $t_2$ $g^{-1} = 0.14$.

The similar pseudopiezoelectric excitation modes (E|E|E) and (E|E|N) lead to similar stress distribution and results, as shown in Figure 2A, F and G. Compared with the mode (E|E|E), the mode (E|E|N) had $\sigma_y$ values between 18 and $-97$ MPa for $Al_2O_3$–PZT composites and 0 and $-51$ MPa for PZT–PZT composites arranged in a parabolic shape. This is usually an indicator for shear stresses. Due to the lack of the frame, the stress type and loading on and in the columns changed.

The results of (E|S|N) and (S|E|N), see Figure 2B–E, showed opposite behavior due to their excitation. According to the materials, $\sigma_y$ for the $Al_2O_3$–PZT composites increased compared with PZT–PZT. Under mode (E|S|N), the maximum tensile stresses within the levers were 94 MPa for $Al_2O_3$–PZT and 42 MPa for PZT–PZT. For both composite types there is a downward opened parabola of shear stresses within the columns[31] and a downward opened hemisphere within the levers. Due to the opposite excitation of levers and columns, the stress behavior in the levers changed in comparison with modes (E|E|E) and (E|E|N), as shown in Figure 2A,F,G.

#### 3.2. Strain Amplification Behavior

The deformation $\varepsilon_y$ was determined by measuring the central unit cell geometry before and after pseudopiezoelectric excitation. This deformation is affected by the relative density of the lattice and the active area $q$. Therefore, the unsigned strain amplification $a_y$ (represented by the amount $|a_y|$) is defined as the ratio $\frac{\varepsilon_y}{\varepsilon_y}$. Due to the low strain amplification in the X-direction $a_x$, the focus was set on the deformation in Y, Figure 3.

For the mode (E|E|E), the strain amplification in the Y-direction $a_y$ ranged from $-4.66$ to $-0.68$, with a maximum of $-4.66$ for $t_2$ $g^{-1} = 1.00$, Figure 3.

The mode (E|S|N) showed an increase in strain amplification with increasing $t_2$ $g^{-1}$. A maximum of 12.1 was determined at $t_2$ $g^{-1} = 0.48$ for PZT–PZT composites. Comparing both composite types PZT–PZT ($a_y$PZT = 12.1) and $Al_2O_3$–PZT ($a_y$PZT = 5.9), the lower strength Young’s modulus of the PZT frame allowed a two times larger strain amplification $a_y$ than $Al_2O_3$. The mode (S|E|N) showed the opposite values of (E|S|N), similar to a mirroring at $X = 0$.

The strain amplification of mode (E|E|N) had a maximum of 5.47 for PZT–PZT composites and 1.42 for $Al_2O_3$–PZT composites at $t_2$ $g^{-1} = 0.26$, Figure 3.

Figure 3. Strain amplification $a_y$ in Y-direction depending on slenderness $t_2$ $g^{-1}$. 

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4. Discussion

The influence of Young’s modulus on the deformation behavior and strain amplification was calculated for the two frame materials Al2O3 und PZT. The lower Young’s modulus of PZT increased the strain amplification $\sigma_y$ up to 85% independent of the excitation mode. The internal tensile stresses decreased by 55% for the modular pseudopiezoelectric excitations modes (E|S|N), (S|E|N), and (E|E|N) in comparison with mode (E|E|E). Based on these results, a frame material with low Young’s modulus leads to minimization of the internal stresses and maximum of the strain amplification $\sigma_y$ with a factor of 12.1. For further investigations, a further reduction of Young’s modulus can lead to additional reduction of the induced stresses and increase in strain amplification. Therefore, other piezoceramics as LNKN,[12,13] metals, or polymers as frame materials can be evaluated.

The active area $q$ was reduced for 68% from mode (E|E|E) to the other modes (E|S|N), (S|E|N), and (E|E|N). Comparing (E|E|E) and (E|E|N) with the same excitation of levers and columns, the strain amplification increased up to 88% by reduction of $q$. Due to the frame excitation in (E|E|E), the deformation and therefore strain amplification of the columns and levers are hindered. So, mode (E|E|N) is preferable for the maximum strain amplification and maximum stress $\sigma_{yy}$ in Y-direction.

At a constant $q = 0.32$, modes (E|S|N) and (S|E|N) had an opposite excitation of the levers and columns. The contraction of the columns supports the expansion of levers, resulting in increased deformation of 55% in comparison with (E|E|N). For (E|S|N) and (S|E|N), the internal stresses and deformations were mirrored at $\sigma_{yy} = 0$. $\sigma_{max}$ was at ±42 MPa and the highest $\sigma_2 = \pm 12.1$ was reached for $t_2 g^{-1} = 0.48$ for PZT–PZT composites. This allowed a maximum extension with minimum influence of the neighboring arms and adjacent cells.

In general, an increase in the slenderness leads to an increase in $|\alpha_y|$. Regardless of the excitation mode and the composite material, a maximum $|\alpha_y|$ was determined for $t_2 g^{-1} = 0.48$. In addition to a maximum strain amplification, a zero deformation can be observed for (E|E|N), Al2O3–PZT, and $t_2 g^{-1} = 0.38–0.69$. The corresponding stress $\sigma_{yy}$ is unequal to zero by increasing the pseudopiezoelectric field, which only affects the PZT blocks. This results in an increase in the internal stress inside the Al2O3 units without a length change due to the piezoelectric activity[36,37] below the elastic yield strength.

A way to achieve zero deformation for the PZT–PZT composites is to combine mode (E|S|N) and (S|E|N) in series or to merge both opposite excitation modes in one structural excitation. Structures with zero Y-deformation can be used to absorb vibrations or loads, which were not converted into Y-deformations. The induced energies can be converted into X-deformations or internal stresses or can be used to generate charges.

Usually this is only found in materials with a very low Young’s modulus and low strength such as polymers, especially elastomers or nanoscale graphitic tubules.[14,15] However, the composites of the investigated modular building blocks are characterized by a high Young’s modulus and high strength, thus enabling an extended range of applications, especially of macroscopic and lightweight elements. Among other things, this effect can be used for novel implant types or scaffolds according to Biggemann et al.[38] to support healing by piezoelectric activation of the cells. Other possible applications are energy transformers and as absorbers of vibrations.

5. Conclusion

In this article, the influence of structural and material properties on strain amplification was investigated using simulations. Pseudopiezoelectric excitation of the modular cellular composites of Al2O3 and PZT were analyzed for four different modes (E|E|E), (E|S|N), (S|E|N), and (E|E|N). The deformation of individual parts could be Expansion (+$\alpha$), Shrinkage ($-$+$\alpha$), or Neutral $\alpha = 0 K^{-1}$.

The influence of Young’s modulus, the active part $q$, and slenderness $t_2 g^{-1}$ on the stress distribution $\sigma_{yy}$ and the deformation in load direction was investigated. Regardless of the excitation mode and the Young’s modulus of the frame, the highest strain amplification $\alpha_y$ of 12.1 was obtained at $t_2 g^{-1} = 0.48$ for PZT–PZT composites and an opposite excitation of the struts at mode (E|S|N).

Increasing the Young’s modulus of the frame reduced $\alpha_y$ and increased the induced internal stresses. By minimizing the active part $q$, $\alpha_y$, and $\alpha_2$ are also increased.

In addition to the desired strain enhancement, zero stretching of the structures in a special excitation case as well as by a combination of opposite excitation (E|S|N) can be achieved based on the results. Structures with zero deformation can be used to absorb vibrations without the vibrations causing deformation of the structures themselves.

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