Numerical analysis of mechanical properties of an infill structure used in 3D printings

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The paper presents results of a numerical analysis focused on an identification of mechanical properties of an element created using Fused Deposition Modelling additive manufacturing technique (FDM). There are presented a description of technology of the 3D printing, numerical model created by using finite element method (FEM), as well as some problems referred to estimation of the mechanical properties of the printout. The main point of the research was a study of relationship between properties of the rectangular infill structure (described in the micro scale) and the global values of selected mechanical properties of the part (described in macro scale). The numerical models of infill was created by applying the ABAQUS 6.12-1 software. The scope of the study involved tests performed in linear elastic limit of the material behaviour by applying uniaxial compressive load and two types of boundary conditions. Also, three alternative methods for identification of mechanical properties of the infill structures were presented. The results of the study of relationship between the density of infill structure and the Young’s modulus of the printout were presented and discussed.

**Key words:** rapid-prototyping, 3D printing, FDM, Young modulus, FEM.

1. INTRODUCTION

3D printing is one of the techniques used for the direct conversion of a 3D numerical model (created using the CAD design technique) to its physical prototype. Initially, the 3D printing was used to create some physical visualizations of models. Currently, the 3D printing plays an increasing role in the prototype production and the small batch production. Apart from conventional processes such as milling, the 3D printing gives an opportunity for some rapid production of elements as well as for examination in terms of their functionality without the necessity to run some complex production facilities. Plastics are the main materials used for the 3D printing, e.g. especially popular are ABS (acrylonitrile-butadiene-styrene), PLA (Polylactic acid), nylon or Laywood (fabric, wood-like, composite wood and plastics). Less conventional materials are resins, rubbers, metals or even concrete [1÷3].

1.1. Technology of 3D printing

In contrast to traditional forming methods, the 3D printing is an additive manufacturing technology. The element is formed by adding the material without any shaping or removing it. Due to the use of different building materials and technologies, several printing techniques can be distinguished. Especially popular are stereolithography (SLA), fused deposition method (FDM), selective laser sintering (SLS) or MultiJet Modelling (MJM). The most commonly used method as well as the cheapest form of the printing (both in terms of the printer cost and the operation cost) is the FDM [4]. Layer by layer, the 3D model is produced by extruding small flattened strings of molten material. Printer nozzles heat the material to the molten point. The thermoplastic is heated into their glass transition temperature and is then formed by an extrusion head. Numerical controlled printer’ head produces a layer of the prototype on the platform in the printout XY plane. Moreover, to prevent against the fall down of the non-supported material at some specific places, where the contour of the next layer goes significantly over the actual one, some support material is placed. When forming of a layer is completed, the platform is moved down (to one level in the vertical direction defined as Z).

Performed downward move of the platform corresponds to thickness of the produced single layer. After the performed downward moves, cycles are repeated to produce other layers of the product, until a whole element is created [5, 6]. According to the paper [1], it could be interpreted that emerging 3D part has a form of a laminate of horizontal layers. In some more detail description, each of the considered layers (except of the initial and the final ones) consists of perimeters and an infill. Perimeters are made to get the most accurate shape of the external surfaces. The infill is introduced to stiff these surfaces. It is worth noticing that density of the infill, as well as height and a pattern of the printed layer can influence significantly the quality and the mechanical properties of this printed product.

1.2. Mechanical properties of 3D printouts

Basic mechanical properties of the 3D printouts such as the yield strength and the tensile strength or the compressive strength are given both by producers of formed materials and producers of the printers. Furthermore, mechanical properties are often presented only in one of the directions of formed material. In-between them, the highest value of tensile strength is frequently presented [3]. However, the 3D printout is an orthotropic material which mechanical properties depending on the printout orientation and its parameters [1, 7, 8]. In consequence, technological parameters such as the printout’s orientation in space, temperature of the printer’s nozzle, speed of the nozzle motion and density of the printout infill can influence the mechanical properties (as the strength, for example) of the whole product. In addition, some post-printing processes as thermal processing and ionising radiation are extra methods of increasing mechanical durability of a printed element [7, 9].

Mechanical properties such as Young’s modulus are calculated, according to the Hooke’s law (on the assumption of the linear-elastic deformation):

\[ E = \frac{\sigma}{\varepsilon} \]  

where: \( \sigma \) – normal stress, \( \varepsilon \) – strain (relative deformation).
Normal stress can be defined in any intersection perpendicular to the axis of the tensile/compressive load. Supposing its uniform distribution, this stress can be calculated as:

$$\sigma = \frac{P}{S} \tag{2}$$

where: $P$ – tensile or compressive force, $S$ – initial area of the cross section.

According to [1, 7, 8] each of the 3D printout should be treated as orthotropic material (an orthotropic model), i.e. properties are dependent on the directions of the load. Mechanical properties are described by material constants: the Young’s moduli, the Poisson’s ratios and the shear moduli. They are calculated for the principal directions of the printing, i.e. the first and the second are parallel to the tracks of the printer’s head (axes “1” and “2”), as well as the third is perpendicular to the printing layers (axis “3”). Material constants are used to compose the elasticity matrix describing the mechanical properties of the orthotropic material [10]:

$$
\begin{bmatrix}
1 & -\nu_{12} & -\nu_{13} \\
-\nu_{12} & E_1 & 0 \\
-\nu_{13} & 0 & E_3
\end{bmatrix}
$$

where: $E_1$, $E_2$, $E_3$ – Young’s moduli referring to the principal directions, $\nu_{ij}$ – Poisson’s ratios referring to the principal directions (deformations in the $j$-th direction, with load imposed in the $i$-th direction), $G_{12}$, $G_{31}$, $G_{23}$ – shear moduli referring to the principal directions.

According to the condition of matrix symmetry (3), the following relationships should be used [10]:

$$
\begin{align*}
\frac{1}{E_1} - \frac{\nu_{12}}{E_2} &= \frac{\nu_{13}}{E_3} = 0 \\
-\frac{\nu_{12}}{E_2} &= \frac{1}{E_1} - \frac{\nu_{23}}{E_3} = 0 \\
\frac{\nu_{13}}{E_3} &= \frac{1}{E_1} - \frac{\nu_{31}}{E_2} = 0 \\
0 &= 0 \\
0 &= \frac{1}{G_{23}} \\
0 &= \frac{1}{G_{31}} \\
0 &= \frac{1}{G_{12}}
\end{align*}
$$

1.3. Finite element model of the printout

Literature analysis has shown that there is no unique way used to model 3D printouts, as well as skeletal systems [11], which have similar geometry to them. Some variants of the modelling methods can be found in [1, 12÷14] where the considered printouts were treated as systems of singular trabeculars (beams) created by the printer’s head.

The paper [12] presents a numerical structure modelled as Timoshenko’s beam that is subjected to numerical tensile load. Rigid elements were used to model the contact between the filaments. The paper states that the proposed type of the modelling can be used in the case when tensile load is set up along one of the axes parallel to the printout’s plane.

The paper [14] proposes the structure of infill created by using 3D tetrahedron elements with the second order shape functions (C3D8). The results of numerical uniaxial compressive tests are agreed with the ones obtained through experiments. Deformations were correlated with physical experiments. The study points out that some disparity of 0.02% can be found between the deformations calculated by using finite element method (FEM) and deformations obtained through experimental tests in UTM (Universal testing machines).

Some models created on the base of the theory of laminate were presented in [1, 13]. Authors have assumed that the considered 3D printout should be treated as a laminate structure. A set of layers have been put one by one and permanently connected [10]. Each singular layer of the printout was treated as a singular layer of the laminate. Every next layer was rotated by an angle of 90° in relation to the previous. Finally, layers were modelled as solid elements.

Analysing the literature referring to the mechanical properties identification of the printout structure, one can distinguish empirical, analytical and numerical approaches [15]. To model the 3D printout its mechanical properties can be treated as an isotropic model [16] or estimated by applying homogenization methods [17]. This last one requires to construct an implicit representation of an effective mesoscale geometry. This representation of mesoscale geometry and material of the printed structure should be homogenized into at macro scale by applying an integral equation formulated on the base of Green’s function. It is also worth noting that printout structure can be also treated as porous material that demands to use method presented in [18, 19].

2. GEOMETRICAL MODEL OF THE INFILL

The geometrical model of the infill of the printout was created by applying the Autodesk Inventor software [19]. The model consists of 12 layers. Each layer is composed of parallel filaments directed at the angle 90° with respect to the previous one (Fig. 1). Every layer was obtained through a singular pass of the printer’s nozzle. The height of the layer is 0.5 mm. The principal dimensions of the analysed model are: 6.35 mm (horizontal direction), 6.35 mm (transverse direction) and 5.86 mm (height) respectively (Tab. 1, Fig. 2). The proposed geometrical model was a modified version of the previous one described in [14]: the number of layers is increased from 3 to 12 considered and the number of the filaments is decreased from 10 to 6. Additionally, in order to apply given boundary conditions, the external filaments located in the first and last layer were trimmed on the height of 0.02 mm.

According to the idea proposed in [14], it was assumed that modelled material is homogeneous and isotropic (the Young’s modulus equals 1517.85 MPa and the Poisson’s ratio is 0.33) [1].

![Fig. 1. The geometrical model of infill](Rys. 1. Model geometryczny wydruku)
are realized by: a) applying constant displacement of the surface of the model along the vertical axis “Z” \((U_Z = 0.002 \text{ mm})\) and fixing its two other displacements \((U_X = 0, U_Y = 0)\) [10]; b) applying encastre boundary conditions to the base of the model \((U_X = 0, U_Y = 0, U_Z = 0)\) (Fig. 4).

3.2. Numerical model of a printout with boundary conditions of type B

Boundary conditions of type B were proposed to perform compressive load induced by the given force. To obtain the required displacement \((U_Z = 0.002 \text{ mm})\) a set of iterative calculations was performed and required force was estimated \((F_Z = 25 \text{ N})\). On the base of this value a pressure corresponding to this force was calculated. This pressure was applied to the surface of the model and the base the model was encastred \((U_X = 0, U_Y = 0, U_Z = 0)\) (Fig. 5).

4. RESULTS OF NUMERICAL RESEARCHES

4.1. Estimations of the Young’s Modulus

Results of numerical researches of 3D printout were obtained by using three methods described in the subsection 4.1.1÷4.1.3. The values of the Young’s moduli \(E_1, E_2, E_3\) corresponding to the mechanical properties of the infill were determined along three axes \(X, Y, Z\) respectively. Axes \(X\) and \(Y\) describes the printout plane. Axis \(Z\) is perpendicular to the printout plain. The Poisson’s ratios are estimated to identify the relationship between the transverse deformation (along the axes \(X\) or \(Y\)) and the longitudinal one (along the axis \(Z\)). Values of the relative deformations were obtained for the boundary conditions of type B. Equation (4) was used to calculate values of the shear moduli in the principal directions \((X, Y, Z)\), as well as values of the Poisson’s ratios.

4.1.1. Method first (method #1)

According to the first method, Young’s modulus was estimated by applying boundary conditions of type A. Using the Equation (1) and maximum value of the calculated principal stress (Fig. 6), Young’s modulus was estimated (it equals to 659.84 MPa). The average strain (relative linear deformation) was calculated as a ratio between the calculated compressive deformation and the nominal height of the model.

4.1.2. Method second (method #2)

According to the first method, Young’s modulus was estimated by applying boundary conditions of type B. Using the Equations (1)÷(2) and maximum value of the calculated principal strain (Fig. 7), Young’s modulus was estimated (it equals to 618.52 MPa).

3. NUMERICAL PRINTOUT MODEL

The numerical model of the infill was created with use of the ABAQUS 6.12-1 software [19]. The printout was subjected to uniaxial compressive loads. In order to calculate its mechanical properties, the Young’s moduli and Poisson’s ratios were calculated in each principal direction. Two types of boundary conditions were used to enforce the uniaxial compressive load (chapters 3.1 and 3.2). Finite elements of type C3D10 (the solid, tetrahedron with 10 nodes) were used to create the numerical model. According to [14], the average size of a finite element was 0.3 mm (that allows to obtain a numerically stable model). The numerical model of the printout was composed of 102165 elements and 163897 nodes.

3.1. Numerical model of a printout with boundary conditions of type A

Boundary conditions of type A were proposed to perform compressive load induced by the given displacement. Boundary conditions

Table 1. Proposed parameters of the geometrical model

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Size, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D)</td>
<td>0.70</td>
</tr>
<tr>
<td>(x)</td>
<td>1.05</td>
</tr>
<tr>
<td>(y)</td>
<td>1.05</td>
</tr>
<tr>
<td>(h)</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Fig. 2. Considered dimensions of the geometrical model  
Rys. 2. Wymiary modelu geometrycznego wydruku

Fig. 3. The numerical printout model  
Rys. 3. Model numeryczny wydruku
Fig. 4. The model with the boundary conditions of type A
Rys. 4. Model, na który nałożono warunki brzegowe typu A

Fig. 5. The model with the boundary conditions of type B
Rys. 5. Model, na który nałożono warunki brzegowe typu B

Fig. 6. Map of the normal stress, MPa, boundary conditions of type A
Rys. 6. Mapa rozkładu naprężeń normalnych wydruku, MPa, na który nałożono warunki brzegowe typu A

Fig. 7. Map of the vertical displacements, mm, boundary conditions of type B
Rys. 7. Mapa rozkładu przemieszczeń wydruku, mm, na który nałożono warunki brzegowe typu B
4.1.3. Method third (method #3)

According to the third method, Young’s moduli were estimated by applying boundary conditions of type A. Using the Equation (1) and maximum value of the calculated principal stress and maximum value of the calculated principal strain Young’s modulus was estimated (it equals to 635.38 MPa). It is worth noticing that obtained value is similar to the previous ones.

4.1.4. Comparison of the obtained results

Applying compressive load along given directions and using the above described methods of Young’s modulus estimation, three values of the Young’s modulus $E_1$, $E_2$, $E_3$ and Poisson’s ratios were estimated (Tab. 2, 3).

4.2. Simplified model

In this considered subsection, an alternative simplified model of the 3D printout structure was proposed. This model was created on the base of the following considerations. Focusing on the element printed by use of a 3D printer, one can notice that it consists of a great number of individual filaments rigidly connected. As a result, when a detailed numerical model is considered (i.e. the one that describes all details of all the filaments of the considered printout presented in the chapter 3), the complex model should be formulated. Numerical researches of this model require an enormous and extremely long calculation time. To reduce the time of calculation, a simplified model is proposed. It was assumed that mechanical properties of this simplified model are identical to those presented in the subsection 4.1 (for the method #2) and satisfied the Equation (4). Obtained values was shown in Table 4.

This simplified model was modelled as a rectangular prism. Its shape is identical to the global shape of the considered infill. A volume of material of the simplified model equals 105 mm$^3$. It is 56% less than in the accurate model (model presented in the section 2). The volume of material in the accurate model is 236,3 mm$^3$. Mechanical properties of this prism were shown in Table 2. To perform numerical researches similar loads and boundary conditions were applied [14].

To calculate relative error of deformation between proposed structures was used:

$$\delta_\mu = \frac{x - x_0}{x_0}$$

where $x$ – displacement obtained in the simplified model, $x_0$ – displacement obtained in the accurate model.

<table>
<thead>
<tr>
<th>Method</th>
<th>Young’s modulus, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2535.04</td>
</tr>
<tr>
<td>2</td>
<td>643.18</td>
</tr>
<tr>
<td>3</td>
<td>292.43</td>
</tr>
</tbody>
</table>

In all of the performed tests, obtained relative error values are lower than 0.02% for the vertical direction (direction perpendicular to the printout plain) and 2.56% for the transverse direction (parallel to the printout plain).

4.3. Relationship between the infill density and Young’s modulus

It was assumed that there is a straightforward relationship between the density of the infill and the Young’s modulus of the element. To verify this assumption, the impact of the infill density on the value of the Young’s modulus was investigated numerically by applying the method #2 (see the subsection 4.1.2). Calculations were performed for the geometrical model consisted of 12 layers (Fig. 1) by changing distances measured between the neighbour filaments of the printout (distances $x$ and $y$ are given in Figure 2). Calculated variation of the infill density is shown in Figure 9.
5. CONCLUSIONS

The scope of the study involved: estimations of the Young’s modulus, presented the simplified model and term relationship between the infill density and the Young’s modulus.

Values of the Young’s modulus were obtained by using third methods estimations and performing numerical simulations. On the base of the obtained results we concluded that the assumed boundary conditions have significant impact on obtained results. It is worth noticing that variability calculated in the direction placed perpendicular to the printout plain is relatively small. Moreover, values of the Young’s modulus are more variable in directions that are parallel to the printout plain.

We stated that proposed simplified model is numerically effective. The values of the displacements obtained for the simplified model were comparable to these calculated for the accurate model. The relative error was less than 0.1% for the displacements perpendicular to the printout plain. However, for the transverse direction, this error was higher, it equals 2.5%. The most important advantage of the simplified model is the decreasing number of the calculations this error was higher, it equals 2.5%. The most important advantage of the simplified model is the decreasing number of the calculations performed. It was also clarified that when a complex model with a higher number of filaments is considered, that it is almost impossible to calculate it without specialised computer having high power capacity.

The infill density has a significant impact on the value of the Young’s modulus. This relationship is not linear, especially in the range of infill density 30% to 70%.

The future development of the study will involve: a) estimation of the influence of the number of layers on the numerical stability of the FEM model, b) experimental verification of the presented numerical model.

ACKNOWLEDGEMENT

Calculations were carried out at the Academic Computer Centre in Gdańsk, Poland.
Analiza numeryczna właściwości mechanicznych wypełnienia stosowanego w wydrukach 3D

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Słowa kluczowe: szybkie prototypowanie, wydruk 3D, FDM, moduł Younga, MES.

1. CEL PRACY

Drukowanie 3D to technologia używana do bezpośredniej konwersji modelu 3D powstałego przy użyciu projekturnych CAD (z ang. computer aided design) do fizycznego modelu prototypu. Ze względu na wykorzystywanie różnych materiałów budulowych oraz technologii nanoszenia wyróżniamy kilka metod drukowania przestrzennego: metoda stereolitografii (SLA), metoda osadzania stopionego (FDM), selektywne spiekanie laserowe proszków (SLS) czy przyrostowe nanoszenie stopionego fotopolimeru akrylowego (MJM). Najbardziej popularne techniki, tzw. „drukarki laserowe” to techniki laserowe (SLS) i stereolitografii (SLA). Drukowanie 3D to technologia używana do bezpośredniej konwersji modelu 3D powstałego przy użyciu technik projektowych CAD (z ang. computer aided design) do fizycznego modelu prototypu. Ze względu na wykorzystywanie różnych materiałów budulowych oraz technologii nanoszenia wyróżniamy kilka metod drukowania przestrzennego: metoda stereolitografii (SLA), metoda osadzania stopionego (FDM), selektywne spiekanie laserowe proszków (SLS) czy przyrostowe nanoszenie stopionego fotopolimeru akrylowego (MJM). Najbardziej popularne techniki, tzw. „drukarki laserowe” to techniki laserowe (SLS) i stereolitografii (SLA).

2. MATERIAŁ I METODYKA BADAŃ

Badany przez autorów model geometryczny wypełnienia wydruku 3D składa się z 12 warstw włókien ułożonych krzyżowo. Każde włókno o średnią D = 0,7 mm odpowiada pojedynczej ścieżce wyładowania prądów wypełniających wydruk. Pręty wypełniające, stosowane w badanym detalu i wykorzystywane w prętach wydruku 3D, mają średnicę D = 0,7 mm. Wartości wytrzymałości na rozciąganie wydruku, wytrzymałości na skurcz i współczynników Poissona wyznaczono na podstawie symulacji. Wartości te uzyskano na podstawie symulacji. Wartości te uzyskano na podstawie symulacji. Wartości te uzyskano na podstawie symulacji. Wartości te uzyskano na podstawie symulacji. Wartości te uzyskano na podstawie symulacji. Wartości te uzyskano na podstawie symulacji.

3. WYNIKI I ICH Dyskusja

Na podstawie przeprowadzonych badań zaproponowano 3 metody wyznaczania modułu Younga wypełnienia wydruków 3D.

Metoda 1 — w wyniku próby ściskania otrzymano rozkład naprężeń normalnych w badanej strukturze. Wyliczona z zależności (1) wartość modułu Younga wynosi 659,84 MPa.

Metoda 2 — referencyjną wielkością liczbową obserwowaną podczas próby ściskania była wartość maksymalnych przemieszczeń występujących w badanej strukturze. Wykorzystując zależność (2) do wyznaczenia naprężeń normalnych oraz zależność wyznaczająca z wzoru (1), wyliczono wartość modułu Younga wynosi 618,52 MPa.

Metoda 3 — referencyjną wielkością liczbową obserwowaną podczas próby ściskania była wartość maksymalnych przemieszczeń oraz naprężeń normalnych występujących w badanej strukturze. Wykorzystując zależność (1), wartość modułu Younga wynosi 635,38 MPa.

Badania powtórzono dla 3 głównych kierunków orientacji włókien. Wartości odkształceń uzyskano na podstawie symulacji. Zaproponowany przez autorów model zastępczy dla struktury wypełnienia wydruku 3D zmniejsza liczbę elementów użytych do analizy oraz skracza czas obliczeń. Struktura składająca się z pojedynczych włókien została zastąpiona bryłą o takich samych wymiarach zewnętrznych.

4. PODSUMOWANIE

W przeprowadzonych badań wynika, że:

– każda z zaproponowanych metod dostarcza przybliżone wartości modułu Younga wyznaczonego w kierunku prostopadłym do płaszczyzny wydruku,

– wartości przemieszczeń uzyskane w modelu uproszczonym są porównywalne z modelem nieuproszczonym, błąd względny dla przemieszczeń prostopadłych do płaszczyzny wynosi poniżej 0,1%.