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Research paper

Experimental investigations on mechanical properties of 3D-printed tensegrity-inspired metamaterials based on 4-strut simplex module

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Abstract: The present study is focused on experimental investigations of mechanical properties of 3D-printed tensegrity-inspired metamaterials. Tensegrity systems have many advantageous features, such as: light weight, high stiffness-to-mass ratio, controllability, inherent attributes of smart structures, and unique mechanical behaviour. They may be applied not only in macro-scale, but they can also be used to create cellular mechanical metamaterials and lattices in various scales. Metamaterials are understood here as human-designed artificial materials, which do not exist in nature, and whose mechanical properties result from the morphology of the inner structure rather than from chemical or phase composition. Experimental studies on tensegrity metamaterials manufactured using 3D printing techniques are hardly present in the literature. This paper presents results of uniaxial compression tests carried out on a number of 3D-printed tensegrity-based modules corresponding to the metamaterial cells, differing in the manufacturing technology, parent material, and size. The following observations were made during the tests: one of the most important parameters that has a direct impact on the results is the elongation at break of the parent material; any inaccuracies at the production stage greatly affect the mechanical behaviour of the structure; it is crucial to ensure a free deformation consistent with the infinitesimal mechanism mode of tensegrity; a post-critical behaviour of the struts was clearly visible in the performed tests.

Keywords: tensegrity, metamaterial, additive manufacturing, 3D printing, laboratory tests

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1. Introduction

Recent years have brought a fast development of novel systems for engineering applications, such as: artificial materials with untypical behaviour, adjustable systems with controllable mechanical properties, or smart materials and structures. The main goal, which has guided the researchers in their search for novel solutions, has been to obtain enhanced behaviour of systems used in emerging modern applications in civil and related engineering areas.

The present study focuses on one of such novel structural systems, which has a great potential to be used in innovative engineering applications, namely tensegrity systems. The concept was first developed by Buckminster Fuller [1] and Kenneth Snelson [2], who defined the term "tensegrity" by using a combination of two words: "tension" and "integrity". They introduced a definition of a structural principle, where a system of isolated compressed members is inside a continuous net of elements in tension. For the purpose of this paper, tensegrity systems are defined as trusses with a special configuration of cables (elements in tension) and struts (compressed members) which form a statically indeterminate structure in stable equilibrium. Tensegrity structures have infinitesimal mechanisms, which are balanced with self-equilibrated systems of normal forces, further referred to as self-stress states [3–5], which do not depend on external loading or boundary conditions. Contrary to finite mechanisms, which relate to arbitrary geometrical instabilities of the structure, infinitesimal mechanisms describe local geometrical instabilities within infinitesimal displacements.

Tensegrity systems have many advantageous features, such as: light weight, high stiffness-to-mass ratio, controllability, inherent attributes of smart structures, free geometry shaping, and unique mechanical properties. To inherent properties of smart tensegrity structures belong: self-control, self-diagnosis, self-repair, and active control [5]. Changes of self-stress forces in structural members of tensegrity make it possible to influence mechanical properties of these extraordinary structures.

Tensegrity structures may be applied not only in macro-scale [6,7], but they can also be used to create cellular mechanical metamaterials and lattices in various scales (Fig. 1). Metamaterials are understood here as human-designed artificial materials, which do not exist in nature [8,9]. These composite systems exhibit many unique features, e.g.: negative Poisson's ratio, vanishing shear modulus, negative compressibility, negative stiffness, or extremal mechanical properties, which result from the morphology of their inner structure rather than from chemical or phase composition of the parent material.

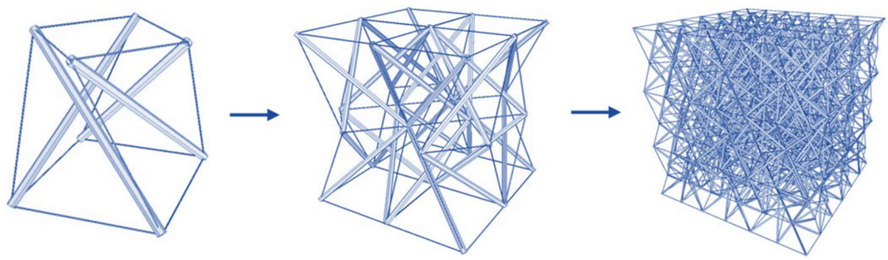


Fig. 1. Tensegrity metamaterial: cell – supercell – lattice

Tensegrity metamaterials were proposed for the first time by Fraternali et al. [10] and afterwards developed in [11, 12], where the authors demonstrated that they have a great potential in engineering applications, e.g. as sensors and actuators in structural health monitoring (SHM) and damage detection systems. De Tommasi et al. [13] focused on the mass and morphological optimization of tensegrity-inspired metamaterials. A new method for creating 3D tensegrity lattices from truncated octahedron cells was proposed by Rimoli and Pal [14] and extended by Salahsoor et al. [15]. Wang et al. [16] developed lightweight tuneable metastructures consisting of prismatic tensegrity modules. Modano et al. [17] analysed different configurations of novel tensegrity lattices. Automatically assembled tensegrity lattices were proposed by Zhang et al. [18] for large scale structures. Ma et al. [19] investigated tensegrity systems with metal rubber-based struts, exhibiting good energy absorption and tuneable dynamic properties. Liu et al. [20] proposed a new approach for generation of tensegrity metamaterials with varying inner architectures. Bauer et al. [21] studied impact protection systems and adaptive load-bearing structures based on tensegrity.

Tensegrity-inspired lattices and metamaterials have various possible application areas. They have a great potential to be used in all applications where high energy absorption is required [14, 21], such as seismic protections systems, vibration damping elements, etc. They might also be used as lightweight structural elements with an inner structure of a tensegrity lattice [5], thus obtaining structural systems with reduced weight and enhanced mechanical behaviour.

This study is focused on investigating mechanical properties of 3D-printed tensegrity-inspired metamaterials with the use of experimental testing. It presents results of uniaxial compression tests carried out on a number of 3D-printed tensegrity-based samples – single modules corresponding to the cells of the discussed lattices – differing in the manufacturing technology, the parent material, and the cell size.

Previously, the authors have studied mechanical properties of tensegrity-inspired metamaterials and lattices using theoretical models [5, 22–24]. In [22] they demonstrated that tensegrity metamaterials exhibit smart properties as well as negative Poisson's ratio. In [5, 23, 24] they studied extremal mechanical properties of tensegrity-based cellular systems. It should be highlighted that all those theoretical models concerned pure tensegrities, that is pin-jointed systems. Here, due to the additive manufacturing technology, the tested systems have rigid connections, which make the tested structures less compliant. However, as can be seen from the results presented in this study, they still behave as tensegrity systems and maintain most of the features of pure tensegrities.

The main aim of this work is an experimental assessment of mechanical behaviour of the 4-strut simplex-based cells of a tensegrity-inspired metamaterial and a preparation of the basis for further research, including selection of the most suitable additive manufacturing technique and indication of the desired properties of parent materials. The theoretical research justifies the approach adopted in this paper, as the mechanical properties of metamaterials are reflected in the analysis of the modules [5]. Similarly, the adopted medium scale of the tested samples allows extrapolation of features to other scales.

The research on 3D-printed tensegrity systems is still at an early stage, with only a few published papers on additively manufactured tensegrity-inspired metamaterials [25–28]. Experimental studies of tensegrity modules manufactured using 3D printing technique are hardly present in the literature. Therefore, in order to apply tensegrity metamaterials or lattices on a wider scale in the future, much more studies need to be done.

2. Additive manufacturing of tensegrity

Additive manufacturing (AM), commonly known as 3D printing, is a technology that makes it possible to obtain real objects using the computer aided design (CAD) or a digital 3D model. The history of this technology dates back to the early 1980s, when Hideo Kodama invented the first rapid prototyping device [29]. The first commercial AM technique, namely stereolithography, was developed by Charles Hull in 1984 [30]. In this technique, the layers of the parent material are added by curing photopolymers with ultraviolet (UV) lasers. Hull defined it as: "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed" [30]. Thanks to the rapid technological progress of recent decades, the AM technology has been a subject of multiple transformations and currently, there are different techniques available.

Tensegrity metamaterials can be fabricated using various techniques, which, in general, may be divided into three categories [31]: ink-based, light-based, and powder-based techniques.

Ink-based technology consists in depositing the parent material on a flat substrate, e.g. by melting a filament and extruding it through a nozzle. There are two techniques which are commonly used: Fused Deposition Modelling (FDM) and Direct Ink Writing (DIW). In FDM [32] a thermoplastic material is heated till melting, then extruded through a nozzle, and cooled down to solidify. In spite of being a popular, commonly available, and relatively cheap technique, it has two serious disadvantages: a weak bond between consecutive layers strongly affects mechanical properties of the printed object, moreover, rapid cooling can cause shrinkage of the deposited material. The DIW technique [33], on the other hand, uses viscoelastic or viscoplastic ink in a syringe which is extruded through a nozzle under external pressure. This method produces rather soft structures that need to be post-processed in order to obtain higher stiffness.

Light-based technology is based on a photopolymerization process, which makes it possible to produce finer features than the ink- and powder-based techniques. It uses either a UV light or a laser source directed into a photopolymer resin. The most popular light-based technique is Stereolitography (SLA) [34], which consists in selective solidification of the liquid resin through a photopolymerization reaction. Another technique suitable for fabrication of tensegrity metamaterials is Two-Photon Lithography (TPL), also known as Direct Laser Writing (DLW). TPL [35] allows for printing of 3D microstructures with high resolution by using a nonlinear dependency of the polymerization rate on the irradiating light intensity.

Powder-based technology uses a laser source to fuse powder particles together, either by melting or by sintering. In this technology, there are three main factors that have impact on the print quality: shape, size, and distribution of the powder. The most popular powder-based technique is Selective Laser Sintering (SLS) [36]. It uses a high-power heating source (laser) to sinter or melt a powder polymer, resin or metal in a heated powder bed, layer after layer. Another commonly known technique is Selective Laser Melting (SLM) [37], which is one of the most popular AM techniques used for commercial fabrication of metallic structures. Here, the printing process is carried out in a special chamber filled with gas, in order to minimize the oxidation risk.

To fabricate tensegrity metamaterials or lattices, we can use any of the techniques mentioned above [25]. While selecting the AM technique, several aspects need to be considered: structural scale, required properties of the parent material, size and expected properties of the fabricated system, etc. Although the research on 3D-printed tensegrity systems is still limited, a fast development of the AM technology visible in the past years may soon create possibilities for applying such systems in real engineering applications, such as: acoustic, vibration and shock energy damping systems, lightweight structural elements, seismic protection systems, 3D fillings of traditional structural elements, etc. [5].

3. Test stand and samples

Samples of tensegrity-based cells considered in this study were manufactured using three different AM techniques, belonging to two categories: light-based and powder-based technology. The ink-based technology is, according to the authors' experience, the least suitable for this kind of application due to its disadvantages mentioned in the previous section.

The following designations of the AM technique and the parent material are used in the presented research:

A.1 – SLA, resin no. 1 (E = 2.2 GPa, f_t = 46 MPa, elongation at break 51%),
A.2 – SLA, resin no. 2 (E = 1.5 GPa, f_t = 33 MPa, elongation at break 48%),
A.3 – SLA, resin no. 3 (E = 2.6 GPa, f_t = 61 MPa, elongation at break 13%),
B.1 – SLS, powder no. 1 (E = 1.85 GPa, f_t = 50 MPa, elongation at break 11%),
C.1 – PolyJet (modified SLA), material no. 1 (E = 2.3 GPa, f_t = 53 MPa, elongation at break 17%),
C.2 – PolyJet (modified SLA), material no. 1 (E = 3.0 GPa, f_t = 60 MPa, elongation at break 15%),
C.3 – PolyJet (modified SLA), material no. 1 (E = 2.0 GPa, f_t = 50 MPa, elongation at break 25%),

where E is an elastic modulus of the parent material and f_t is its tensile strength.

All tested modules were 3D-printed by a professional company, on industrial printers. PolyJet is an industrial name for an AM technique that is similar to SLA, but uses different types of resins.

Tensegrity-based modules of various sizes were tested (Fig. 2). The module designations are as follows:

s2 – 4-strut simplex inscribed into a cube of edge length a = 20 mm,
s3 – 4-strut simplex inscribed into a cube of edge length a = 30 mm,
s4 – 4-strut simplex inscribed into a cube of edge length a = 40 mm,
s5 – 4-strut simplex inscribed into a cube of edge length a = 50 mm.

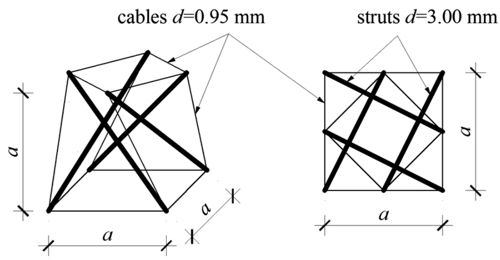


Fig. 2. Geometry of the 4-strut simplex module

In all tested modules the struts had a diameter of 3.00 mm and the diameter of cables was 0.95 mm, thus achieving a cable-to-strut stiffness ratio $k = (EA)_{\text{cable}} / (EA)_{\text{strut}} = 0.1$, where A is a cross-sectional area of the member [5].

The tests were conducted in two series. In the first series, 7 samples of tensegrity-based cells s3, each made of a different parent material (from A.1 to C.3) were tested. After this series, three parent materials were chosen for further research: A.2, A.3, and C.3. In the second series, for each selected parent material 28 samples of tensegrity-based cells were manufactured: 7 samples per each cell size (from s2 to s5). Together, in the second series, 84 samples of 3D-printed tensegrity-based cells were tested. Fig. 3 shows a photograph of all tensegrity-based samples tested within Series 1, while Fig. 4 presents selected samples of Series 2.

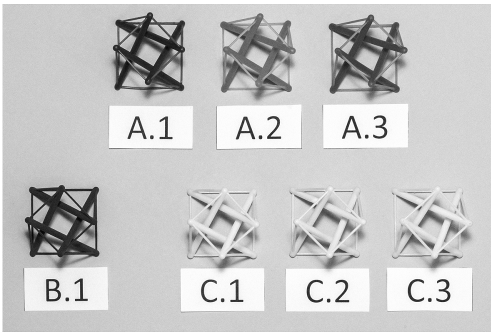


Fig. 3. Series 1 – tensegrity-inspired cell samples

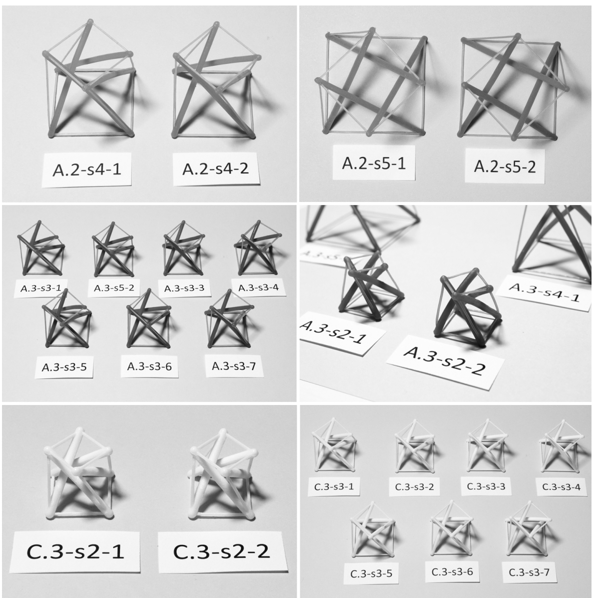
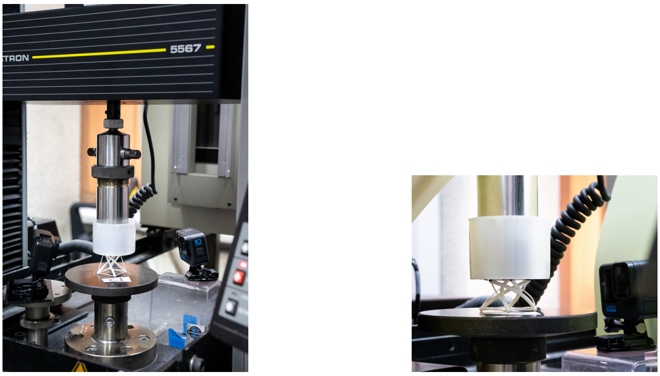


Fig. 4. Series 2 – selected tensegrity-inspired cell samples

3D-printed samples of tensegrity-based cells were subjected to uniaxial compression tests in the universal testing machine INSTRON 5567, with the measurement accuracy of 0.5 N. Photographs of the test stand are presented in Fig. 5. A displacement control method with a velocity of 2 mm/min was applied. The results – force corresponding to the displacement in time – were obtained directly from the universal testing machine.



(a) (b)

Fig. 5. Test stand: a) universal testing machine with a sample; b) sample under compression

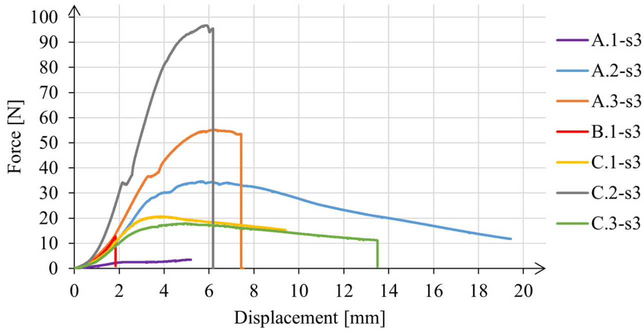
The tests were designed in such a way that the upper base of the module could rotate freely around the vertical axis of the sample, thus enabling a free movement consistent with the infinitesimal mechanism of tensegrity. In order to achieve it, the upper joints were greased and could slide on the plastic element attached to the machine head.

4. Compression test results

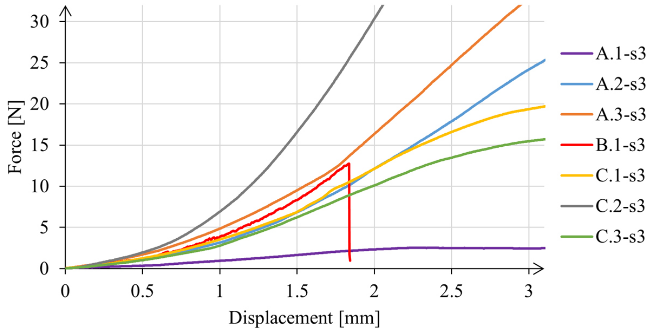
In the first test series, seven samples of 3D-printed tensegrity-based cells were axially compressed in the universal testing machine. The aim of this first series was to study different behaviours of seven parent materials with varying physical and mechanical properties, in order to choose three most suitable materials for further research. Results obtained from Series 1 are presented in Fig. 6.

Analysis of the force-displacement curves (Fig. 6) reveals significant differences in mechanical behaviour of the tested samples. The highest load-bearing capacity was achieved by sample C.2-s3, the lowest – by A.1-s3. Several samples were destroyed abruptly (e.g. A.3-s3, B.1-s3, C.2-s3), while several exhibited ductile behaviour and continued to carry the force even after reaching the maximum load (e.g. A.2-s3, C.1-s3, C.3-s3).

The obtained shapes of the curves are directly related to the properties of the parent materials specified in the previous section. It can be noticed that the samples made of materials with high values of the elongation at break (A.2-s3, C.3-s3) could carry the load much longer than others. On the other hand, the samples made of materials with high values of the elastic



(a)



(b)

Fig. 6. Series 1 – force-displacement curves from uniaxial compression tests: a) full range; b) limited range – zoom on the curves

modulus (A.3-s3, C.2-s3) had the highest load-bearing capacity. The only exception is sample A.1-s3, which carried the lowest load, despite a relatively high elastic modulus of the parent material. This unexpected behaviour was a result of visible inaccuracies in the geometry of the sample related to the manufacturing process.

Figure 7 shows a photograph of damaged samples. It can be noticed that the sample that reached the highest load-bearing capacity (C.2-s3) was destroyed completely in the test – it suddenly exploded. Other samples kept the overall shape of tensegrity, but in each case, at least one element (one of the cables) broke during the test. It seems interesting that some samples (e.g. A.2-s3) continued to carry the load even after losing (in this case – breaking) one of their structural members. No general rule was observed in terms of the kind of cables (cables of the lower base, diagonal cables, and cables of the upper base) that broke.

After careful analysis of the results of Series 1, the authors selected three promising materials for further tests: A.2, A.3, and C.3. The key used in the material selection was as follows. The SLS technique was rejected at this stage due to the brittle properties of material B.1. Out of two materials with a tendency to abrupt damage, one was chosen for further studies, namely A.3. Material A.2 was selected as an example of a material with a very ductile behaviour, and C.3 – as a representative of a PolyJet technique.

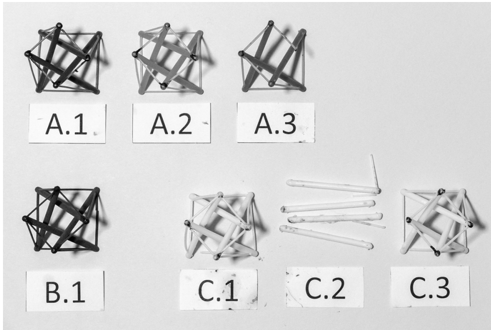


Fig. 7. Series 1 – tensegrity-inspired cell samples after the uniaxial compression test

The second test series was focused on two types of analyses: investigation of the influence of the parent material on the behaviour of the module (Fig. 8), and analysis of the scale effect within each parent material (Fig. 9).

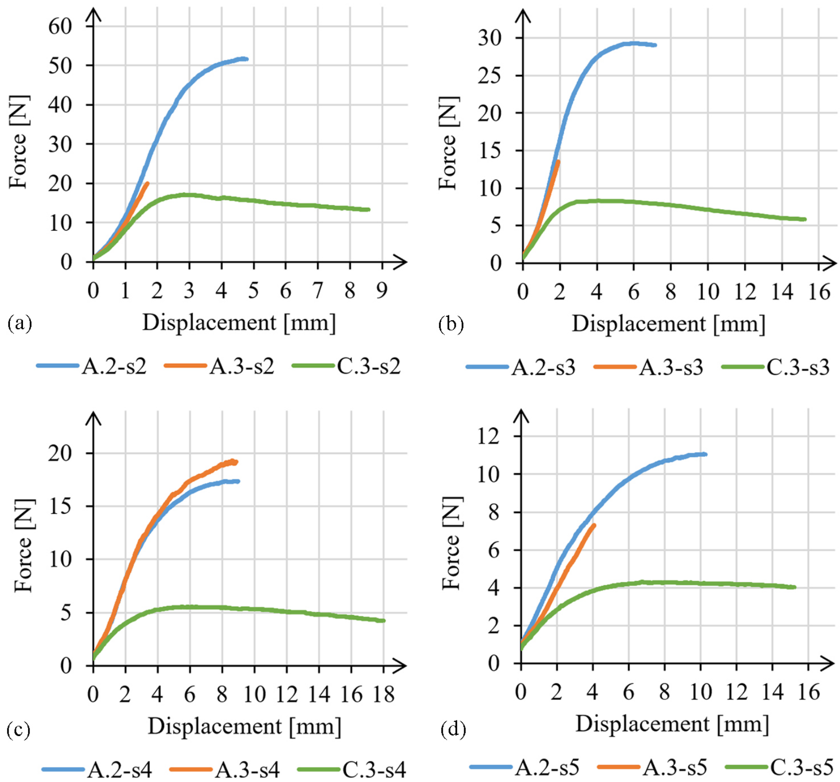


Fig. 8. Series 2 – averaged force-displacement curves from uniaxial compression tests: a) modules s2; b) modules s3; c) modules s4; d) modules s5

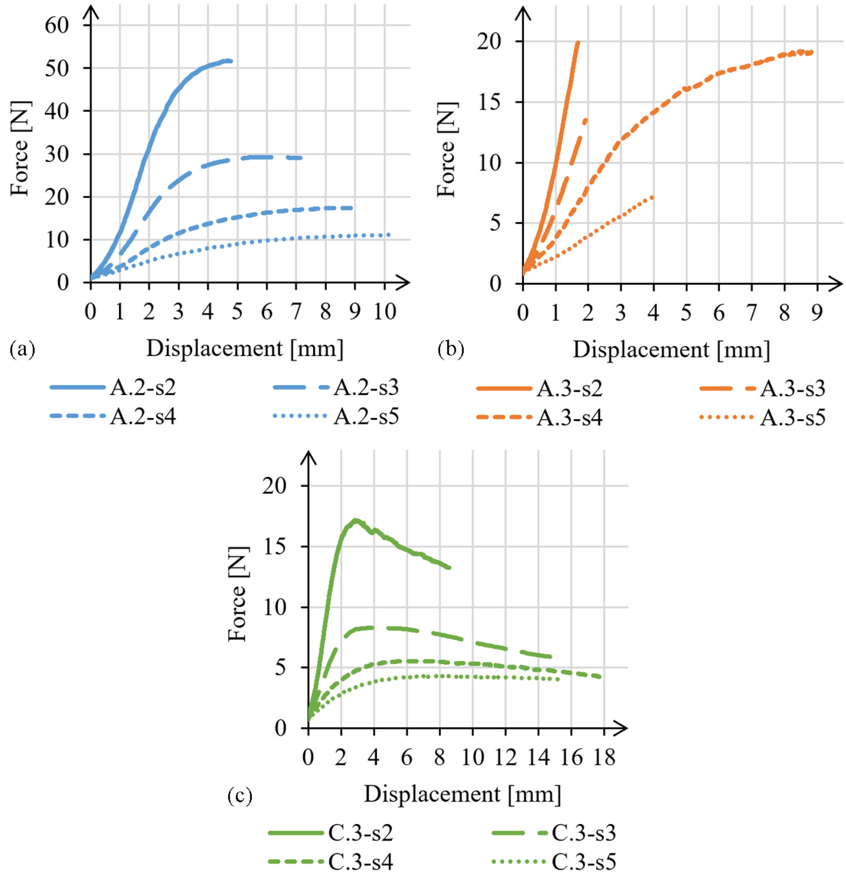


Fig. 9. Series 2 – averaged force-displacement curves from uniaxial compression tests: a) material A.2; b) material A.3; c) material C.3

Figure 8 shows force-displacement curves obtained in the uniaxial compression tests, depicted on four separate diagrams – each for a different geometry. Fig. 9 presents the same curves, but organised in different groups, in order to assess the influence of the module size on the results. All curves presented in Fig. 8 and 9 are averaged results obtained from the tests on seven tensegrity-based cell samples, thus there are visible the differences between these curves and the ones presented in Fig. 6, which depicts curves obtained from single tests.

It can be noticed that the samples made of resins A.2 and A.3 behaved similarly in terms of their stiffness, but reached different values of the maximum load. The parameter that had the biggest impact on this type of behaviour was the elongation at break of the parent material. Samples manufactured using the PolyJet technique exhibited different properties, in spite of having similar mechanical parameters of the parent material declared by the producer. It should be noted that, although the PolyJet technology is similar to SLA, it uses parent materials with slightly different physical properties, and this caused a different behaviour of C.3-based tensegrity samples.

In terms of the scale effect, the obtained results are consistent with the expected behaviour of the samples. The smaller size of the cell, the higher load-bearing capacity of the module was observed. This is not surprising, as all modules had cables and struts with the same diameter, thus, the critical load was reached faster in longer struts (bigger cells).

It should also be noted that all tested tensegrity modules deformed consistently with their infinitesimal mechanisms – the rotation of the upper bases of the modules under compression was clearly visible.

In order to demonstrate that the manufacturing process of tensegrity-based metamaterial cells is repetitive, mean values of force-displacement curves, with standard deviation marked, are presented additionally in Fig. 10 for modules s3. There is no doubt that the 3D printing technique allows for manufacturing tensegrity-inspired items with repetitive parameters.

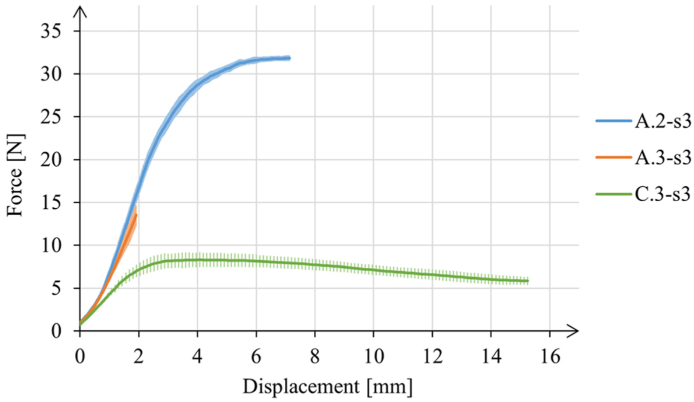


Fig. 10. Series 2 – force-displacement curves from uniaxial compression tests on modules s3: mean values with standard deviation

5. Conclusions

In this study, the authors presented results of experimental tests carried out on cellular tensegrity-inspired lattices in medium-scale. In particular, results of uniaxial compression tests conducted on a number of 3D-printed tensegrity-based samples – single modules corresponding to the lattice cells – were discussed.

The tests were conducted in two series. The aim of this first series was to study various AM techniques and different parent materials with varying physical and mechanical properties, in order to choose the most suitable techniques and materials for further research. The second test series was focused on two types of analyses: investigation of the influence of the parent material on the behaviour of the tensegrity module and analysis of the scale effect within selected parent materials.

Altogether, three AM techniques were checked: SLA, SLS, and PolyJet (modified SLA). The SLS technique was rejected after the first test series due to brittle properties of the parent material. Within two technologies qualified to the second test series, four cell sizes were tested – tensegrity modules inscribed into the cubes with edge lengths from 20 mm to 50 mm.

It should be highlighted that the dimensions of the modules chosen for testing resulted from the technical limitations of the manufacturer. In order to create a real metamaterial, its single cells should be much smaller – in micro- or nano-scale. However, due to high costs and low availability of nano-printing technology, plus problems with laboratory testing in such a small scale, the authors decided to start their research from a bigger scale, which allows for time- and cost-effective tests on a wide range of various systems.

Analysis of the obtained results clearly shows that one of the most important parameters that has a direct impact on the results is the elongation at break. The higher elongation at break of the parent material, the more ductile behaviour of the sample is observed. Nevertheless, a simple comparison of the mechanical properties of parent materials, which are declared by the producers, is not sufficient to prognose the behaviour of the resultant tensegrity-inspired metamaterials.

Another important aspect is the geometry of the sample. Any inaccuracies at the production stage affect the mechanical behaviour of the 3D-printed structure. A good example is a sample made of material A.1, which had visible defects that led to a very poor mechanical behaviour of the printed module. Due to high complexity of tensegrity-based geometries, it is recommended that for each series more samples are manufactured than planned to test, in order to be able to eliminate samples with geometrical defects.

Observations of the samples under compression confirmed that it is crucial to ensure a free deformation consistent with the infinitesimal mechanism mode of the structure, as this is a key feature of tensegrity. Moreover, a post-critical behaviour of the struts was clearly visible in the performed tests.

Taking into account the conclusions from the experimental research presented in this paper, future studies will focus on the local stability of the struts, as well as creating a theoretical model of tensegrity which accounts for rigid joints. Moreover, other types of tensegrity-based modules will be manufactured and tested experimentally, and 3D-printed models of supercells and bigger lattices will be investigated.

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Badania doświadczalne własności mechanicznych metamateriałów tensegrity bazujących na module Simplex 4, wykonanych techniką druku 3D

Słowa kluczowe: tensegrity, metamateriał, techniki przyrostowe, druk 3D, badania laboratoryjne

Streszczenie:

Konstrukcje tensegrity są strukturami prętowo-cięgnowymi o szczególnej konfiguracji elementów, charakteryzującymi się występowaniem mechanizmów infinitezymalnych równoważonych przez stany samonaprężenia (ang. self-stress). Do głównych zalet tych struktur należą: wysoki stosunek sztywności do masy, możliwość zastosowania w systemach rozwijalnych, możliwość sterowania własnościami mechanicznymi, ekstremalne własności mechaniczne. Metamateriały definiuje się jako zaprojektowane i stworzone przez człowieka, niewystępujące w naturze struktury kompozytowe o nietypowych własnościach. O ich cechach decyduje głównie morfologia struktury. Ostatnie lata przyniosły niezwykle dynamiczny rozwój metamateriałów, w których naukowcy widzą szansę na uzyskanie zrównoważonych materiałów o nietypowych własnościach mechanicznych, pożądanych m.in. w wielu obszarach inżynierii lądowej. Badania doświadczalne metamateriałów tensegrity są jednak wciąż we wczesnej fazie. Niniejsza praca koncentruje się na eksperymentalnym badaniu własności mechanicznych metamateriałów tensegrity wykonanych w technologii druku 3D. Przedstawiono wyniki badań jednoosiowego ściskania przeprowadzonych na szeregu próbek tensegrity – pojedynczych modułach odpowiadających komórkom meta-struktur – różniących się technologią wytwarzania, materiałem macierzystym i rozmiarem. Testy zostały przeprowadzone w dwóch seriach. Celem pierwszej serii było zbadanie różnych technik przyrostowych i różnych materiałów macierzystych o zróżnicowanych właściwościach fizycznych i mechanicznych, w celu wybrania najbardziej odpowiednich technik i materiałów do dalszych badań. Druga seria badań koncentrowała się na dwóch rodzajach analiz: badaniu wpływu materiału macierzystego na zachowanie modułu tensegrity oraz analizie efektu skali w wybranych materiałach macierzystych. Łącznie sprawdzono trzy techniki druku 3D: SLA (ang. S*tereolitography*), SLS (ang. *Selective Laser Sintering*) i PolyJet (zmodyfikowana SLA). Technika SLS została odrzucona po pierwszej serii badań ze względu na kruche własności materiału macierzystego. W drugiej serii przebadano cztery rozmiary komórek tensegrity, skupiając się na obserwacji efektu skali. Przeprowadzone badania wykazały, że w przypadku struktur tensegrity bardzo dużą wagę należy przykładać do dokładności wykonania, gdyż wszelkie niedokładności geometrii wpływają w znacznym stopniu na otrzymane wyniki. Ponadto należy tak planować testy, by zapewnić strukturom możliwość deformacji zgodnie z ich ruchem infinitezymalnym. Podczas badań zaobserwowano też wyraźnie powyboczeniowe zachowanie się zastrzałów, należy zatem zwrócić uwagę na stateczność lokalną tych elementów.

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