CICE 2023 Rio de Janeiro – Brazil 11TH INTERNATIONAL CONFERENCE ON FRP COMPOSITES IN CIVIL ENGINEERING

FRP DECK SYSTEM USING TPMS LATTICE STRUCTURE

Lucija Stepinac, *University of Zagreb, Croatia*, lstepinac@arhitekt.hr
Josip Galić, *University of Zagreb, Croatia*, jgalic@arhitekt.hr
Ana Skender, *University of Zagreb, Croatia,* ana.skender@grad.unizg.hr

ABSTRACT

The 21st-century achievement in structural engineering and architecture will be in combining computer-aided design (CAD) with information technologies, material science, and additive manufacturing (AM) to create optimal 3D-printed mega-scale structures. By observing many objects in nature, it was found that the TPMS (triply periodic minimal surface) pattern is an optimal geometry in terms of minimal surface that separates space into equal volume domains. The mechanical principle governed in bioinspired TPMS structures is implemented into the bridge deck system, resulting in minimizing material consumption to resist the applied load. Compared to traditional FRP decks, the stiffness of TPMS bridge decks increases by 40-60% with the same material properties. Considering the new materials with a reduction in material properties, the stiffness of topology-optimized structures can be surpassed. The results show that a topology-optimized bridge deck with changing material concentrations can have the same stiffness while the mechanical properties are halved. This creates room for new materials, even biocomposites for structural applications in large-scale objects.

KEYWORDS

Polymer; FRP; bridge deck; pedestrian bridge; TPMS lattice; topology optimization

INTRODUCTION

In the last two to three decades, there has been a tremendous increase in the power of computers and the adaptability of software packages for computer-aided design (CAD). In the 21st century, the focus is on linking digital design with production processes [1]. Recent research describes how industrial robots can handle complex architectural forms, reducing the high cost of custom design, manufacturing, and assembly (Figure 1) [2], [3].

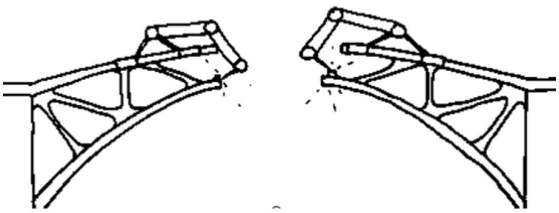


Figure 1: First 3D-printed bridge with robots by MX3D over the Amsterdam canal [2]

Rapid advances in information technologies and robotics have greatly favored the use of 3D printing in large-scale manufacturing [4]. The use of lighter polymer materials in 3D printing technologies is of great interest to researchers today, as they can be used to produce complex geometries. The application of additive manufacturing ranges from small and medium-sized objects to large-scale architectural structures [5]. However, there are still many limitations in terms of standardization, which is needed for wider application in architecture and construction. Additive manufacturing (AM) has evolved over the years, with various production methods to choose from: Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Stereolithography (SLA), Direct Light Processing (DLP) and the technology used in this study - Fused Deposition Modelling (FDM) [6].
Standard materials, as well as a variety of new materials, are drastically changing the direction of design and construction in general. Through observation, computer programming and calculation, we are able to control the behavior of the material to obtain the final geometry of the structural elements. The trend is that the prototypes we will get in the future will resemble biological and natural structures, such as

the structures of bones, plants, tissues, sponges and corals [7]. The idea of simulating forms found in nature is a new facilitation method in construction. Such technology transfer is called bionics, biomimetics, or biognosis. Cellular organisms provide us with examples of how material is concentrated where it is needed most to create optimized structures [8]. The muse for cellular geometries has been found in nature, as many biological structures are porous but with great interconnectivity [7].

By observing many objects in nature, such as the scaled biphotonic structure of butterfly wings and weevils - a great example of symmetric and optimized physical properties - the TPMS (Triply Periodic Minimal Surface) pattern was found [9]. These novel structures (Figure 2) are gaining more and more attention. Their application has been observed in thermal analysis, mechanics, biology, chemical engineering and acoustics [10].

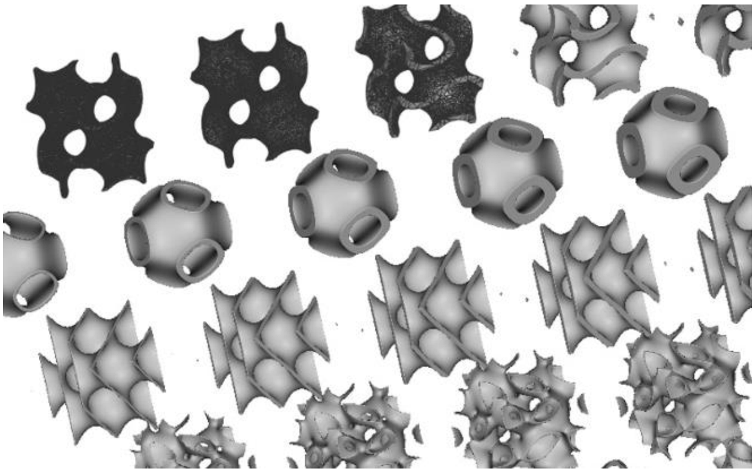


Figure 2: TPMS units

The advantage of choosing TPMS structures is material and energy saving, which is very much vivid in aerospace, automotive and similar industries. TPMS structures are mostly used as a core structure in sandwich panels. Compared to other lattice core structures, TPMS structures show much better performance [11], [12]. Due to the porosity of its structure, TPMS structure can be used wherever energy absorption is required, e.g. connections in structure.

Based on all this, TPMS is considered to be the optimal geometry in terms of minimum surface area, dividing the space into equal volume domains [9]. In a study [13], superior properties of TPMS were found compared to isotropic material.

The application of TPMS in topology optimization has been used in many fields of mechanical engineering. In this study, the same approach is applied from architecture to structural design for secondary structural elements – the deck of pedestrian bridge. The mechanical principle that prevails in natural structures is implemented in the topology optimization of structural elements, using the minimum amount of material to resist the applied load. Since 3D printing has no limitation for the design this approach is universal and customizable depending on the purpose and dimensions of each project.

METHODOLOGY

The prediction of the mechanical properties of TPMS cellular material has been carried out in numerous studies so far and it has been shown that the effective properties are mainly influenced by their morphology [14]. The TPMS unit is mathematically defined by the implicit function and there are endless possibilities for the innovation of new and hybrid formulations. Some of the most common are: Gyroid, Schwarz, Diamond, Split, and Neovius. In this study, the focus was on Gyroid and Schwarz Primitive Structure (Figure 3). All geometries were analysed in flat and arched form. Different unit cell dimensions were compared at the same densification percentage.

This study will compare typical two-dimensional web infill geometry in popular FRP deck panels (Superdeck, Duraspan, EZSpan, Strongwell and sandwich panels with honeycomb and triangular infill) with novel three-dimensional TPMS structure (Gyroid and Schwarz). A 10 mm thick top and bottom flange is defined for all typologies. It is assumed that the flange of novel strucrure is tie-constrained with the TPMS infill geometry, which can be 3D printed in one piece or additionally glued to a sheet made of glass, FRP, metal, or other materials. The results for the sandwich panels were taken from the study [15] and compared with the novel deck system with TPMS geometry. The TPMS structures used are Gyroid and Schwarz Primitive. For all types, the analysis is performed in flat and curved plate geometry.

The dimensions of the deck are 5.0 x 1.8 x 0.2 m for all slabs. Finite element analysis (FEA) is performed with solid 3D elements and nTopology software [16] is used to create the TPMS geometries with a periodic grid block. For the gyroid structure, two different grids are used: 500x500x500 mm and 200x200x200 mm, and for Schwarz structure, a grid of 200x200x200 mm was used. Since the deck height is 200 mm, the gyroid structure is shortened by 150 mm at the top and bottom with the larger grid. The meshing is done separately for the flanges and TPMS lattice, with a uniform size of 10 mm. The connection between the top flange and lattice, and between lattice and the flange is assumed to be fully constrained. The pressure is assumed to be 6 kN/m^2 for the serviceability load combination (1 kN/m^2 for dead load and 5 kN/m^2 for live load). The supports are defined as displacement restraints in three orthogonal directions on both slab sides.

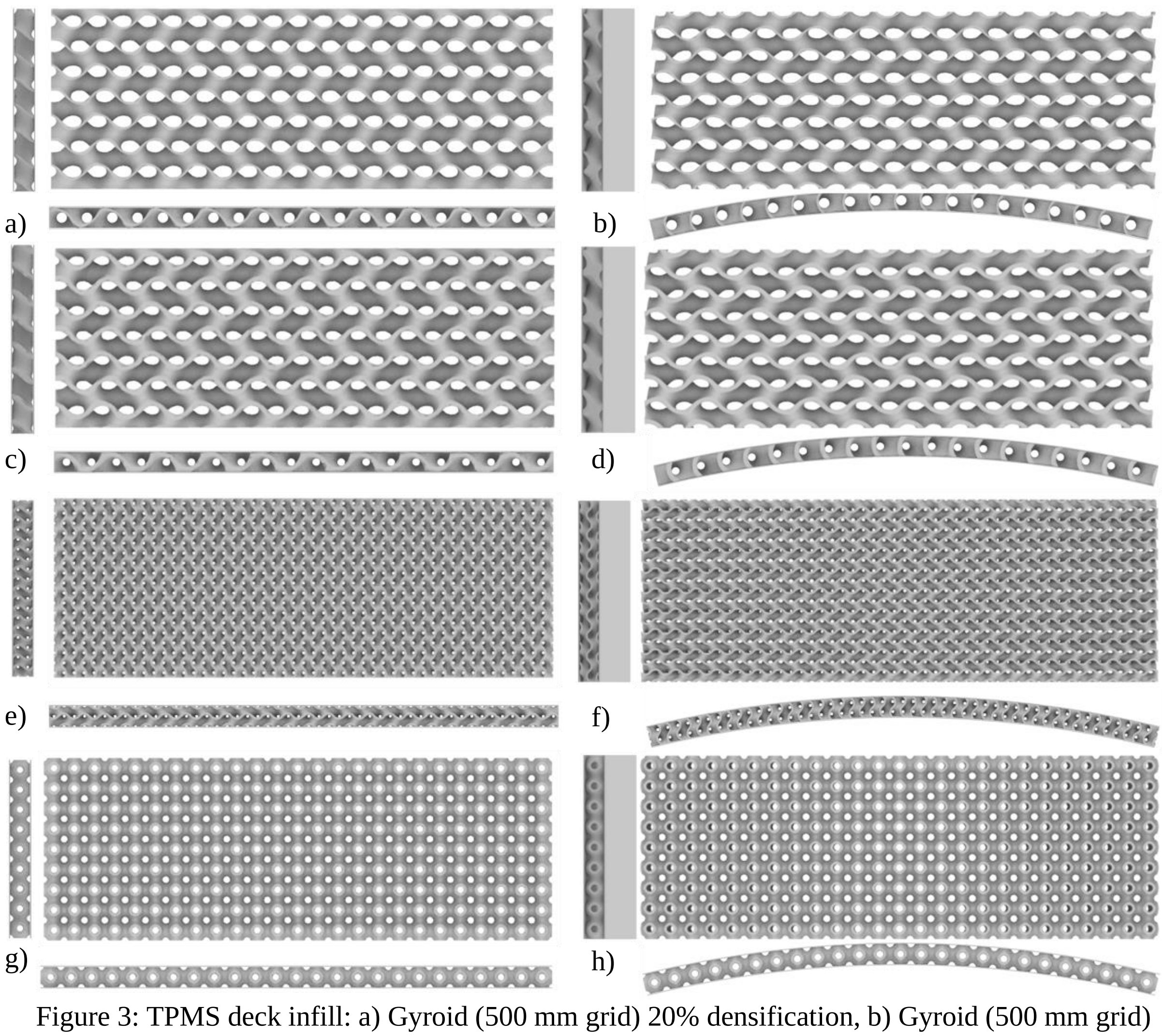


Figure 3: TPMS deck infill: a) Gyroid (500 mm grid) 20% densification, b) Gyroid (500 mm grid) 20% densification in an arch, c) Gyroid (500 mm grid) 35% densification, d) Gyroid (500 mm grid) 35% densification in an arch, e) Gyroid (200 mm grid) 35% densification, f) Gyroid (200 mm grid)

35% densification in an arch, g) Schwarz Primitive (200 mm grid) 35% densification, h) Schwarz Primitive (200 mm grid) 35% densification

The FRP material with a 40% chopped glass fiber content was used for standard sandwich deck systems. The quasi-isotropic properties are defined and the modulus of elasticity is assumed to be 10 GPa. Theoretical assumptions were made for the proposed new TPMS decks, since no specific material was selected. The proposed new TPMS decks were calculated for the quasi-isotropic material to compare with the study and with the filled 3D-printed composite material with a modulus of elasticity of 5 GPa. Similar properties can be achieved for filled ASA or bio-composites PHBV with natural fillers such as hemp, flax or wood fibers [17], [18]. The potential of green additive manufacturing can become even more sustainable through the use of biocomposites [19].

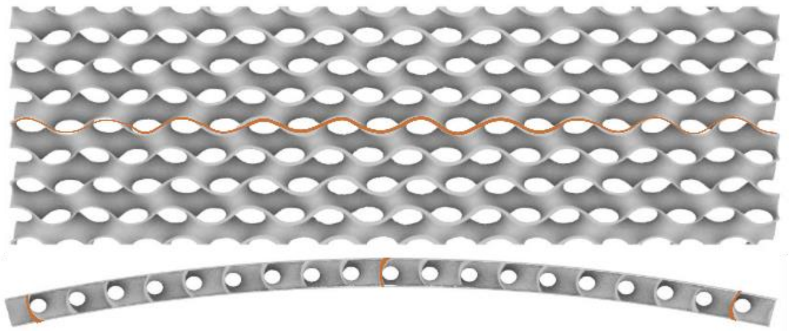


Figure 4: Topology optimization with gyroid structure

The results are presented graphically and the potential of additively manufactured TPMS decks is explained. The comparison is made based on weight and stiffness. 3D printing of polymers with a robotic arm uses a pellet filler, at the end of which is a nozzle of about 5 mm that can pump about 8 kg of material per hour. For the production of one deck, this would result in about 2 printing days. In the production of the 3D printed component, less material waste, energy consumption, and gas emissions from the machines are taken into account. Therefore, the environmental impact of additive manufacturing is demonstrably lower than other production methods.

RESULTS

The unit cell morphology for each TPMS structure was periodically repeated in two orthogonal directions. For a 500x500 mm grid, the number of unit cells is about 40 and for a 200x200 grid, the total number is 225 units.

For the comparison of the results, the density of the FRP material is assumed to be 2000 kg/m^3 and that of the 3D printed material (ASA or bio-composite) is assumed to be 1079 kg/m^3. For each TPMS geometry, the volume and weight were determined. Finally, the static analysis was performed based on the serviceability design criteria. The displacement results were used to quantify the stiffness of each novel deck system and compare it to the conventional FRP decks.

The results show a deck with a smaller gyroid TPMS unit and a deck with a larger (incomplete height) TPMS unit. Geometry from Figure 3c was compared to Figure 3e and geometry from Figure 3d was compared to Figure 3f. The results show almost the same stiffness with a 2% difference in deformation for the same global deck density. This proves that the structural properties are mainly influenced by the densification after morphology is defined. Comparison of two TPMS morphologies: Gyroid and Schwarz Primitive, generated with the same dimensions 200x200x200 and the same total densification of 30%, the results are within a 3% difference in favor of Gyroid TPMS. Compared to the honeycomb sandwich panel and TPMS structure with the same density and material properties, the Gyroid three-dimensional structure has 50% less deflection than the honeycomb 2D sandwich panel, 45% less deflection than Duraspan, 40% less deflection than EZSpan, 48% less deflection than Strongwell, 41%

less deflection than Superdeck and 60% less deflection than the triangular sandwich panel. The results show great potential for TPMS deck compared to the traditional deck systems (Figure 5).

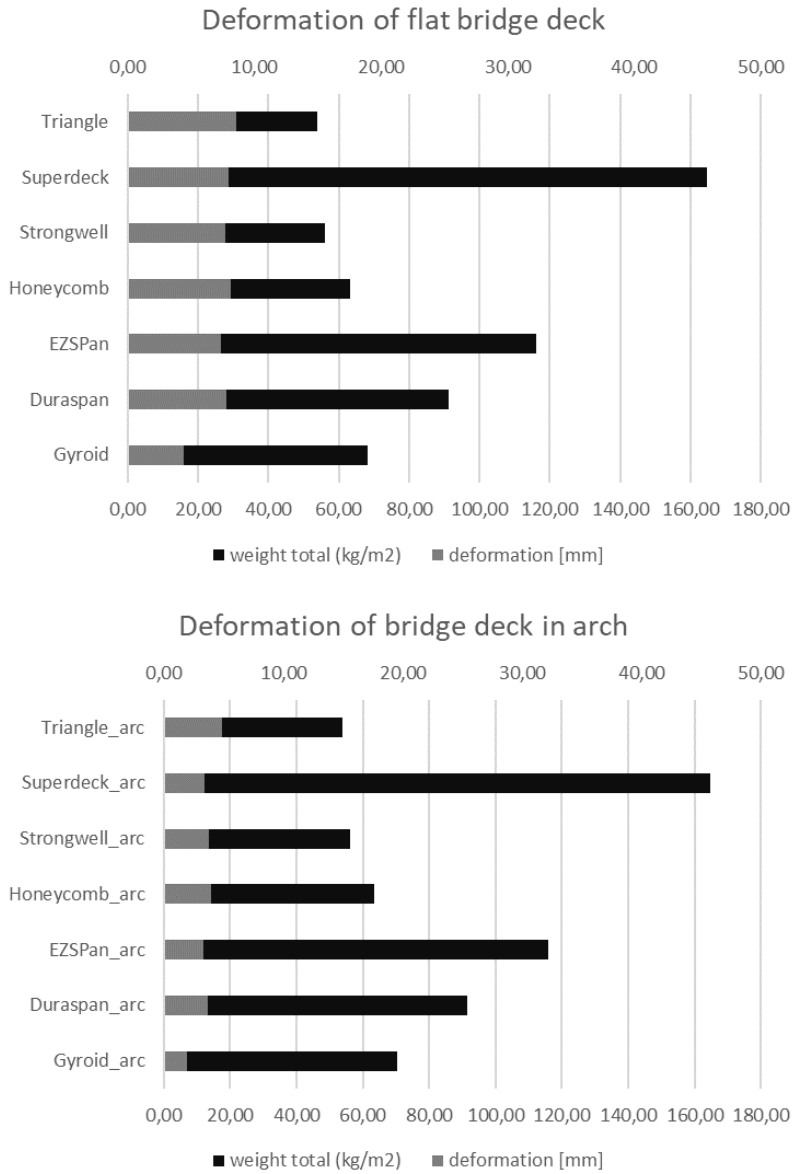
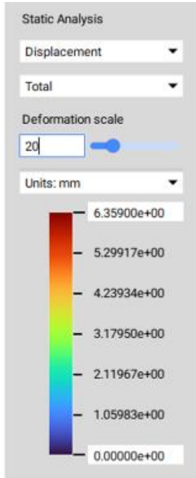
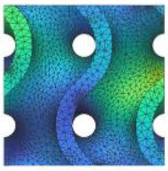


Figure 5: Comparison of Gyroid TPMS deck with traditional deck system. Please note that the bars on the graph represent two distinct value categories: the black bars represent the total weight, while the grey bars represent deformation

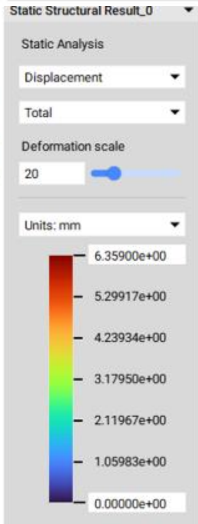
To speed up the time-consuming analysis with more than 20 million elements for the TPMS deck, the process of homogenization was applied and the results of displacements were compared. The homogenization process is applicable for the flat deck but not for the deck in the arch because the TPMS structure has almost the same mechanical properties in the three orthogonal directions. When these material properties are applied in a form other than flat, the TPMS principal axes are changed and are no longer applicable. The overlap of results for flat decks compared to homogenized decks is almost 100% accuracy for the gyroid structure and 98% for Schwarz. The homogenization process can greatly simplify the design process for a simple deck geometry with uniform distribution of units (Figure 6). Based on the morphology type, TPMS material can be classified as orthotropic (Schwarz Primitive) to even isotropic (Gyroid).



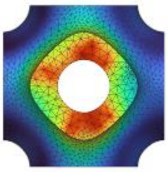
a)



5,71E+09	1,61E+09	1,61E+09	0	0	0
1,61E+09	5,71E+09	1,61E+09	0	0	0
1,61E+09	1,61E+09	5,71E+09	0	0	0
0	0	0	2,05E+09	0	0
0	0	0	0	2,05E+09	0
0	0	0	0	0	2,05E+09



b)



4,22E+08	2,41E+08	1,94E+08	766084	2,33E+06	-242059
2,41E+08	5,21E+08	2,38E+08	-14761,8	446091	332391
1,94E+08	2,38E+08	4,63E+08	672772	3,01E+06	-63306,3
766084	-14761,8	672772	2,69E+08	29826,6	2,68E+06
2,33E+06	446091	3,01E+06	29826,6	2,79E+08	2,28E+06
-242059	332391	-63306,3	2,68E+06	2,28E+06	2,29E+08

Figure 6: Homogenization FEA of: a) Gyroid; b) Schwarz Primitive

In addition, topology optimization was applied to the gyroid deck in an arch. To reduce the overall weight of the structure, the gyroid unit was modeled with a grid of 500x500x500 mm, changing the wall thickness from 10 to 50 mm depending on the von Mises stress values measured from the static analysis of the solid (Figure 7 a). The parallel can be drawn based on weight reduction and reduction in material properties. The optimized TPMS gyroid deck results in an 80 % lighter structure compared to the solid body. The optimized geometry is even 57 % lighter than the uniform TPMS gyroid deck with only 18 % higher deformation. Another comparison can be made based on the material - with the same total volume of the structure (almost double the total weight of the structure) and a 50% degradation of modulus of elasticity the stiffness increases by 23% in favor of the optimized structure and nearly neutral stress distribution within the whole deck (Figure 7 b).

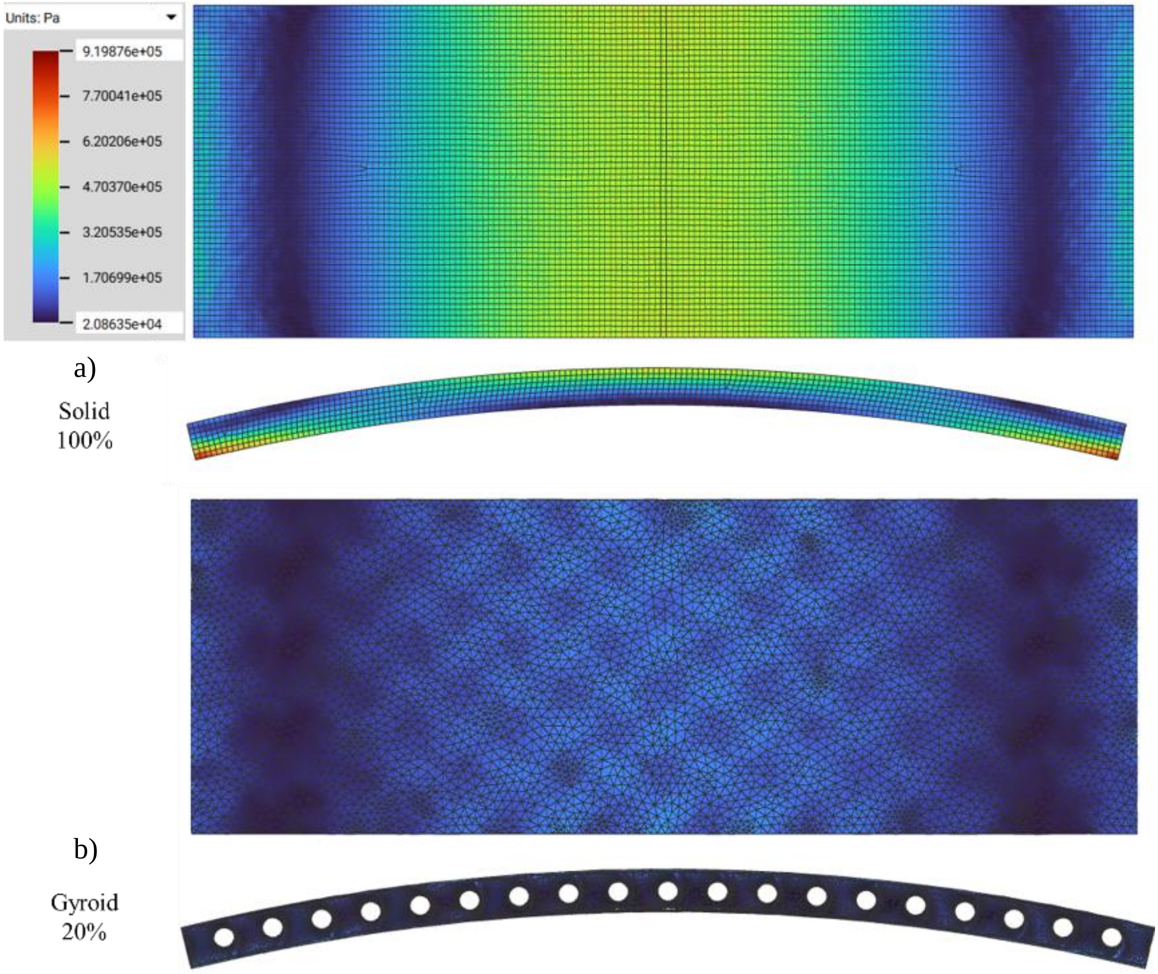


Figure 7: Stress distribution: a) Solid body, b) Topology optimized Gyroid with 20% densification

CONCLUSION

Architects and civil engineers are looking for new ways to improve the building sector by focusing on the global need for sustainability. The TPMS pattern is taken from nature and has been used in the past in the field of mechanical sciences. This research proposes to use it in a similar way for pedestrian bridge decks. A desirable strength-to-weight ratio of the structure is a factor that needs to be considered in the design of the components of the load bearing structure. The mathematically controlled implicit function of TPMS, in addition to the lower weight mentioned above, has improved mechanical properties compared to other lattice structures, has properties of high energy absorption, vibration and ultimately influences the reduction of overall construction costs. A limitation that currently available FRP decks have is the geometric dependence of the shape and infill geometry to mold. This study presented novel approaches to the design and fabrication of optimal composite structures that vary in size, shape and material densification and are freed from the constraints of manufacturing.

Large-scale additive manufacturing of these novel structures has shown great potential, but there are still many challenges that need to be overcome. In particular, issues such as residual stresses, warpage, heat-affected zones, delamination, etc. are common problems in the production of 3D-printed parts. Further research is needed to fully understand these issues and develop effective solutions. Despite these challenges, continued advances in materials and technology suggest that 3D printing will continue to be an important tool for manufacturing and engineering applications in the future.

REFERENCES

[1] I. Gibson, D. Rosen, and B. Stucker, *Additive Manufacturing Technologies; 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. 2015. [Online]. Available: http://link.springer.com/10.1007/978-1-4939-2113-3

[2] Dezeen, "https://www.dezeen.com," 2015. https://www.dezeen.com/2015/12/30/video-interview-robots-worlds-first-3d-printed-bridge-mx3d-joris-laarman-movie/

[3] N. Hack, W. Lauer, S. Langenberg, F. Gramazio, and M. Kohler, "Overcoming repetition: Robotic fabrication processes at a large scale," *Int. J. Archit. Comput.*, vol. 11, no. 3, pp. 285–300, 2013, doi: 10.1260/1478-0771.11.3.285.

[4] B. Khoshnevis, D. Hwang, K.-T. Yao, and Z. Yeh, "Mega-scale fabrication by contour crafting Behrokh Khoshnevis," *Int. J. Ind. Syst. Eng.*, vol. 1, no. 3, pp. 301–306, 2006.

[5] W. Gao *et al.*, "The status, challenges, and future of additive manufacturing in engineering," *CAD Comput. Aided Des.*, vol. 69, pp. 65–89, 2015, doi: 10.1016/j.cad.2015.04.001.

[6] G. Serin, M. Kahya, H. O. Unver, and N. Durlu, "A REVIEW OF ADDITIVE MANUFACTURING TECHNOLOGIES Production of Ti-6Al-4V Alloys Used in Aerospace Industry by Additive Manufacturing View project Deep Learning for Intelligent Manufacturing View project," no. January, 2018, [Online]. Available: https://www.researchgate.net/publication/322745252

[7] L. J. Gibson, "Biomechanics of cellular solids," *J. Biomech.*, vol. 38, no. 3, pp. 377–399, 2005, doi: 10.1016/j.jbiomech.2004.09.027.

[8] L. J. Gibson and M. F. Ashby, "Cellular solids: Structure and properties," *Journal of Biomechanics*, vol. 22, no. 4. p. 397, 1989. doi: 10.1016/0021-9290(89)90056-0.

[9] L. Han and S. Che, "An Overview of Materials with Triply Periodic Minimal Surfaces and Related Geometry: From Biological Structures to Self-Assembled Systems," *Adv. Mater.*, vol. 30, no. 17, 2018, doi: 10.1002/adma.201705708.

[10] J. Feng, J. Fu, X. Yao, and Y. He, "Triply periodic minimal surface (TPMS) porous structures: from multi-scale design, precise additive manufacturing to multidisciplinary applications," *Int. J. Extrem. Manuf.*, vol. 4, no. 2, p. 022001, 2022, doi: 10.1088/2631-7990/ac5be6.

[11] C. Peng, K. Fox, M. Qian, H. Nguyen-Xuan, and P. Tran, "3D printed sandwich beams with bioinspired cores: Mechanical performance and modelling," *Thin-Walled Struct.*, vol. 161, no. September 2020, p. 107471, 2021, doi: 10.1016/j.tws.2021.107471.

[12] A. W. Alshaer and D. J. Harland, "An investigation of the strength and stiffness of weight-saving sandwich beams with CFRP face sheets and seven 3D printed cores," *Compos. Struct.*, vol. 257, no. November 2020, p. 113391, 2021, doi: 10.1016/j.compstruct.2020.113391.

[13] W. Lee, D. Y. Kang, J. Song, J. H. Moon, and D. Kim, "Controlled Unusual Stiffness of Mechanical Metamaterials," *Sci. Rep.*, vol. 6, no. December 2015, pp. 1–7, 2016, doi: 10.1038/srep20312.

[14] D. W. Abueidda, R. K. Abu Al-Rub, A. S. Dalaq, D. W. Lee, K. A. Khan, and I. Jasiuk, "Effective conductivities and elastic moduli of novel foams with triply periodic minimal surfaces," *Mech. Mater.*, vol. 95, pp. 102–115, 2016, doi: 10.1016/j.mechmat.2016.01.004.

[15] L. Stepinac, A. Skender, D. Damjanović, and J. Galić, "Frp pedestrian bridges—analysis of different infill configurations," *Buildings*, vol. 11, no. 11, pp. 1–16, 2021, doi: 10.3390/buildings11110564.

[16] G. Allen, "nTopology Modeling Technology," p. 17, 2020.

[17] W. Frącz, G. Janowski, R. Smusz, and M. Szumski, "The influence of chosen plant fillers in PHBV composites on the processing conditions, mechanical properties and quality of molded pieces," *Polymers (Basel).*, vol. 13, no. 22, 2021, doi: 10.3390/polym13223934.

[18] M. A. Vigil Fuentes, S. Thakur, F. Wu, M. Misra, S. Gregori, and A. K. Mohanty, "Study on the 3D printability of poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/poly(lactic acid) blends with chain extender using fused filament fabrication," *Sci. Rep.*, vol. 10, no. 1, pp. 1–12, 2020, doi: 10.1038/s41598-020-68331-5.

[19] R. Blok, J. Smits, R. Gkaidatzis, and P. Teuffel, "Bio-Based Composite Footbridge: Design, Production and In Situ Monitoring," *Struct. Eng. Int.*, vol. 29, no. 3, pp. 453–465, 2019, doi: 10.1080/10168664.2019.1608137.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.