Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 115-121
doi:10.4028/p-7gwg63

Submitted: 2021-12-01
Accepted: 2022-01-24
Online: 2022-07-22

Influence of Geometric Parameters on Buckling Behavior of 3D Printed Anisogrid Structures

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Keywords: Anisogrid structure; Buckling; Fused Filament Fabrication; CFRP; 3D printing.

Abstract. The present work aims at studying the buckling behavior of lattice structures realized by additive manufacturing technology. To this purpose, carbon fiber reinforced thermoplastic filaments have been used to realize anisogrid structure at different geometric parameters by means of Fused Filament Fabrication technology. Eight configurations were realized varying the rib width and the rib thickness of the structures, and keeping constant the cell height value. Anisogrid structures were tested under compressive load in order to investigate the effect of geometric parameters on strength and specific strength exhibited by the structures. It has been shown that mechanical performances of lattice structures are highly affected by the geometric parameters of the anisogrids.

Introduction

The challenge for the coming years and decades is to prevent pollution for the protection of the planet. Unfortunately, fauna and flora, as well as entire territories, are suffering from the serious, often irreversible, effects related to environmental pollution. One of the main challenges facing the world's leading experts is the one related to reducing environmental pollution caused by gaseous emissions into the atmosphere [1]. In particular, car manufacturers must be compliant to increasingly stringent regulations on consumption which impose the development of new materials and production processes in order to create component that are increasingly lighter, but that guarantee the high performances [2]. For this purpose, new lattice structures have been developed in order to strongly reduce product weights, while maintaining high mechanical properties [3,4]. Lattice structures are used to provide stiffness and strength to compression-loaded components. As far as the development of new materials is concerned, research focused on lightweight materials such as high-performance metal matrix composites, so that the final component could be obtained using conventional metal forming operations. Unfortunately, the manufacturing of lattice structures in lightweight alloy was an expensive process, characterized both by long manufacturing time and a large amount of material waste. In recent years, as a result of overcoming the typical drawbacks of manual operations in terms of productivity and repeatability of the mechanical properties of composite laminates, the interest has mainly turned to carbon fiber reinforced polymers (CFRP) due to the development of automated fiber positioning processes [5,6]. The diffusion of CFRPs, realized using an additive approach in their manufacturing processes, led to the development of anisogrid structures in composite materials, characterized by higher performances and efficiency than those provided by anisogrid structures in lightweight metal alloys [7,8]. Anisogrid structure are lattice structures generated by ±60° inclinated ribs to form hexagons in section.

The typical failure mode of compressive-loaded anisogird structures is buckling [9]. The buckling occurs as the whole structure collapses and the compression resistance is related to the geometric parameters of anisogrid structure, such as cell height, rib width, rib height, rib thickness, winding angle (in case of cylindrical structures) and skin thickness.

Many researches were conducted in order to increase the buckling resistance of lattice structures by the optimization of such parameters. However, most of them concerned the study of cylindrical structures due to the large applications in the aeronautical sector [10,11]. Other researchers refer to flat isogrid, that are lattice structure generated by ribs to form equilateral triangles [12,13]. Anisogrid structures need to be analysed in an in-depth scientific study.

As far as manufacturing processes are concerned, one of the most promising techniques to produce composite parts is the 3D printing. In the last decade, the technology related to additive manufacturing has had a great development allowing the production of composite material components [14,15] with mechanical properties higher than those made of metal alloys. Among all the additive manufacturing technologies, the Fused Filament Fabrication (FFF) technique is certainly the most widespread and reliable for the production of composite material parts and is performed by extruding a thermoplastic filament enriched with short carbon fibers. In the last period even long and hard reinforcements are gaining market share.

High times and high-costs production for anisogrid structures manufactured by fiber-reinforced composite material made FFF technology as an excellent method for the production of such structures. However, this topic is not sufficiently investigated in the literature, since only few previous articles by the authors is available [16]. This work shows that the buckling behaviour of 3D printed composite isogrid structures is strongly related to the moisture absorption of the polyamide matrix; in addition, the increase in the height of the cell leads to a decrease in both the maximum load and the specific maximum load, while the increase in the width of the ribs leads to an increase in both the peak load and the specific maximum load.

As far as anisogrid is concerned, on the other hand, the scientific literature offers only a few research. Totaro et al. [17] investigated the buckling behaviour of curved anisogrid lattice panel (without skin), including multiple hexagonal cells. Santoro et al. [18] analysed prototyped E-glass/polypropylene composite anisogrid lattice structures with the fabrication of circular composite rings and used finite element modeling (FE) to predict the mechanical performance of anisogrid lattice structures. Calibration and validation of the model was performed using the results of mechanical tests.

In this framework, the effect of geometric parameters on the mechanical behaviour of 3D printed anisogrid structures in carbon fiber reinforced polymers requires a more detailed investigation, in order to define which geometric parameters mainly affect the performances of the anisogrid structures. To this purpose, in this paper, different anisogrids in short carbon fiber reinforced polyamide polymer were manufactured by FFF additive manufacturing technology. The structures, realized with different rib widths and rib thicknesses, were tested under compression load. The effect of geometric parameters on maximum load and specific maximum load was investigated.

Material and Experimental Procedures

Material

The material used in the present study was CarbonPA, which is a thermoplastic polyamide PA6.10 matrix reinforced with 20% in weight of short carbon fiber. This material, in form of a 1.75 mm diameter filament, was equipped in the commercial One+400 3D printer, produced by Roboze spa, to manufacture composite anisogrid structures. According to the material datasheet, CarbonPA is characterized by a high ultimate tensile strength, equal to 108 MPa, and elastic modulus of 9.7 GPa; such values are very similar to those exhibited by lightweight metals such as aluminum alloys, but its density is equal to 1.07 ± 0.05 kg/cm^3. Such high mechanical properties make CarbonPA a suitable material to replace metals in many applications characterized by high mechanical performances. CarbonPA filament was heated in an oven at 110°C for 4 h in order to remove moisture absorbed by material before printing and to improve printing quality reducing void formation.

Design and printing process

The FFF printing process was carried out by means of an extruder with a diameter of 0.4 mm. During extrusion operation, the carbon fiber reinforced polyamide was kept in a controlled atmosphere at 70°C. The extrusion was performed at 260°C, by imposing a bed temperature of 80°C in order to avoid detachment of the structures. An infill density equal to 100% was chosen.

The commercial CAD software Rhinoceros was used to design anisogrid structures in order to get exported in .STL format files. The mesh file was imported in a slicing software able to create a .GCODE file for translating the 3D model into instructions for the 3D printer.

A total of 24 anisogrid structures, realized in 8 different configurations, were manufactured. Fig. 1 shows a typical anisogrid structure, characterized by three geometric parameters: rib thickness, rib width and cell height. Rib thickness and rib with was varied from 3 mm to 5 mm and from 4 to 15 mm, respectively. However, in the present study, the cell height value was kept constant and equal to 18 mm. In order to maintain the unsupported length of the structure (as defined in the Euler's critical load formula) unchanged, the size of the sides parallel and perpendicular to the longitudinal ribs was kept constant and equal to 99.5 mm in length and 75 mm in width for anisogrid with rib width of 3 mm and 107 mm in length and 89.5 mm in width for anosigrid with rib with equal to 5 mm.

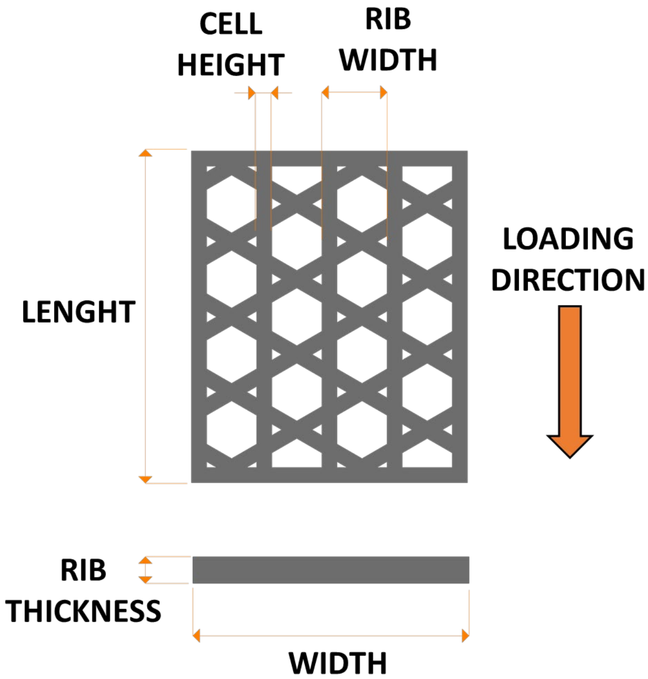

Figure 1: Geometrical parameters of an anisigrid structures

Table 1 summarizes the values of geometric parameters investigated in the present work.

Table 1: Geometric parameters values imposed for the manufacturing of anisogrid structures

Rib width [mm]	Rib thickness [mm]	Cell height [mm]	Weight, w [g]
3	4	18	13.7
3	8	18	30.6
3	10	18	39.4
3	15	18	56.6
5	4	18	23.4
5	8	18	48.1
5	10	18	58.5
5	15	18	88.0

Then, anisogrid structures were weighted by means of an analytical balance. Table 1 also shows the weights of each anisogrid structure.

Compression test

The universal testing machine MTS 810 was used to perform compression tests in order to investigate the buckling behavior of anisogrid structures. The structures were tested so that the direction of load application was parallel to the length of the anisogrid, as shown in Fig. 1. During buckling tests, the load (P) and the displacement (S) were acquired. Moreover, in order to investigate the specific resistance, the ratio between the peak load (Pmax) and the weight (w) was considered. Slow platen speed was imposed (2 mm/min) in order to avoid undesired inflection of the structures.

Result and Discussion

Fig. shows typical load vs. displacement curves recorded during buckling tests on of anisogrid structures, obtained at different rib width and rib thickness values. Irrespective of the geometric parameters, it can be seen that the load increases with displacement up to a peak value (Pmax) reached at to the onset of buckling of structure. Table 2 summarizes the maximum buckling load values measured at different geometric parameters.

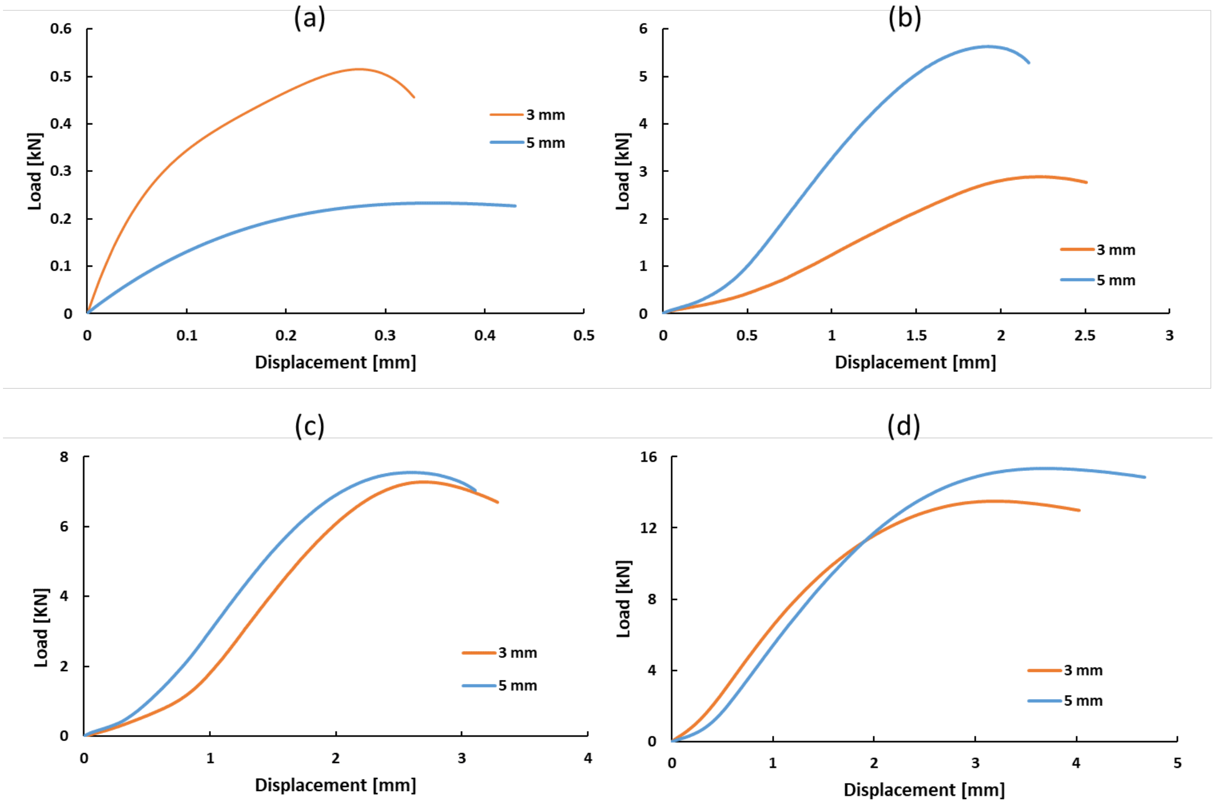

Figure 2: Effect of geometric parameters on typical load vs. displacement curves of anisogrid structures tested under compression load: rib thickness of (a) 4 mm; (b) 8 mm; (c) 10 mm; (d) 15 mm (cell height of 18 mm)

The buckling load and the maximum buckling load are highly affected by the geometric parameters of the structure. Specifically, as far as the effect of the rib thickness on the buckling behaviour of anisogrid is concerned, it can be observed that, for given rib width and cell height values, the maximum load increases with rising rib thickness. Furthermore, as the rib thickness increases, the anisogrid structures increasingly withstand the buckling load, as shown by the higher values of the displacement before failure. The peak values of buckling load generally tends to increase also with increasing rib width, when a rib thickness value is imposed. A negligible influence of rib width can be observed when the lowest rib thickness value is considered.

Table 2: *Max load and specific max load for all anisogrid configuration.*

Rib Thickness x Rib Width Configuration	Max Load [kN]	Max Load / Weight (kN/kg)
4 x 3	0.5	38.0
4 x 5	0.2	9.9
8 x 3	2.9	94.4
8 x 5	5.6	117.0
10 x 3	7.3	184.7
10 x 5	7.5	129.0
15 x 3	13.5	238.9
15 x 5	15.3	174.3

In order to also take into account the weight of each anisogrid structures, typical specific buckling load versus displacement curves obtained during the compression test were plotted (Fig. 3).

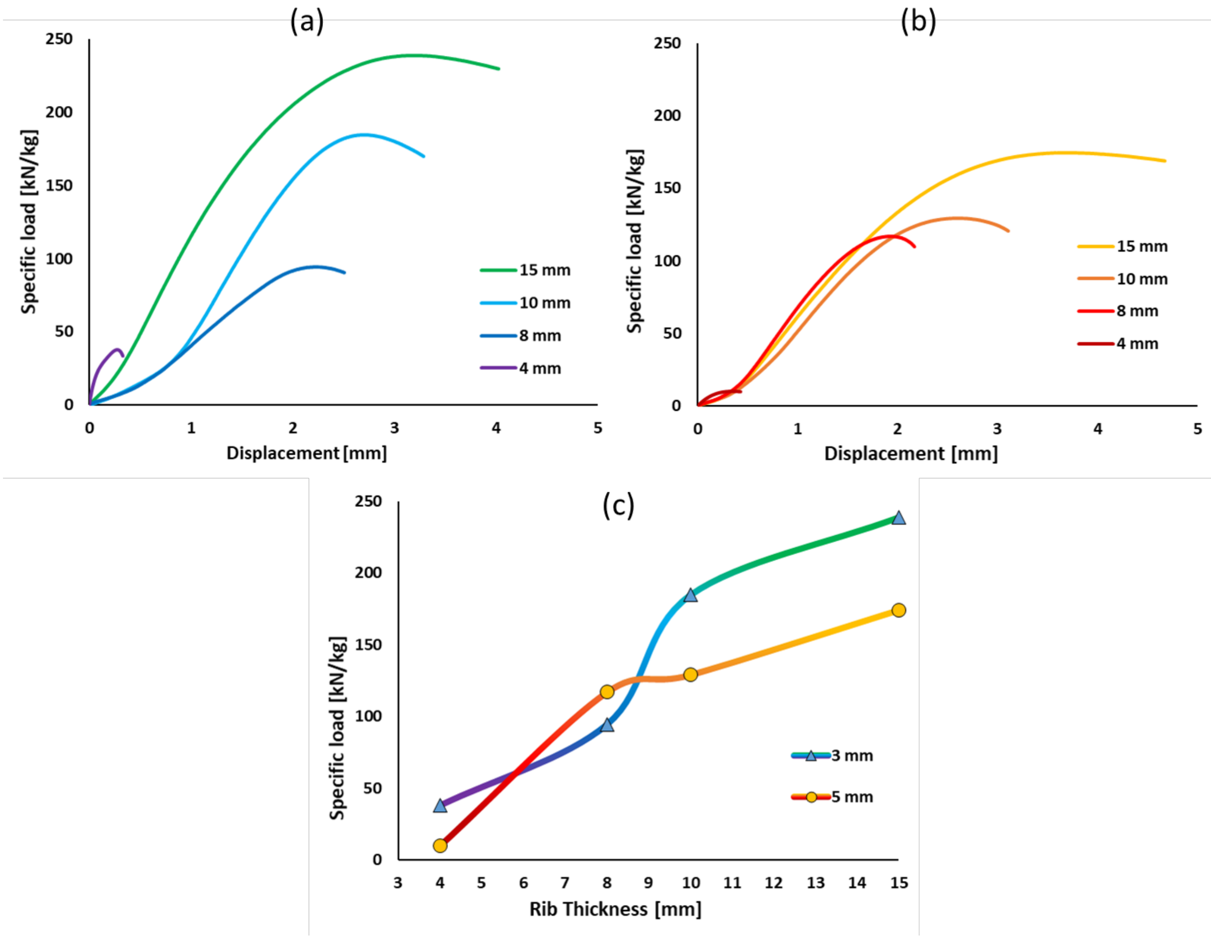

Figure 3: Specific load vs. displacement curves of buckling behaviour for configuration with rib width of 3mm (a), 5mm (b) and specific load vs. rib thickness behaviour curves for configuration of 3 mm and 5 mm (c).

Consistently with what observed for the load behaviour during the buckling test, the specific load also increases with displacement up to a peak value, at the beginning of the buckling phenomenon. Considering the effect of geometric parameters on the specific compression load, it can be seen that anisogrid structures, realized with a rib width of 3 mm, are characterized by higher performances than those obtained with a rib width of 5 mm (Fig. 3c) for all rib thickness values except for the 8 mm one.

As far as the effect of rib thickness is concerned, it is worth to notice that Pmax/w ratio increases with rib thickness both for configurations with rib width of 3 mm (Fig. 3a) and 5 mm (Fig. 3b), denoting that the rise in rib thickness results in an improvement in both strength and specific strength. Such results are consistent with those obtained by Di Pompeo et al. in [19] and Wang and Abdalla [9].

Conclusion

In the present paper, 3D printed composite anisogrid structures in polyamide reinforced with 20% in weight of short carbon fiber were additively realized by means of Fused Filament Fabrication technology. Eight different anisogrid configurations were manufactured varying the rib width and rib thickness values. The weight of each anisogrid structures was also measured before testing to analyse the specific load as a function of geometric parameters. Then, the structures were tested under compression load in order to evaluate the effect of geometric parameters on buckling behaviour of structures. The main outcomes can be summarized as follows:

- The load recorded during buckling test increases with displacement up to a peak value reached at to the onset of buckling;
- The increase in rib width leads to an increase in buckling load and in specific buckling load;
- The rise in rib thickness results in an enhance in both buckling load and in specific buckling load, even though such effect is less marked as the specific load is taken into account;
- Anisogrid configurations which lead to the highest buckling load are different to those resulting in the highest specific load.

In light of these results, 3D printing for composite materials demonstrates an excellent ability to make high-performance anisogrid structures. This can lead to a considerable diffusion of this production technology for the realization of high-performance products for sectors such as motorsport, aeronautics and aerospace.

Acknowledgements

The Grant of Excellence Departments, MIUR-Italy (ARTICOLO 1, COMMI 314-337 LEGGE 232/2016) is gratefully acknowledged.

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