

## Article

# Systematic Experimental Evaluation of Function Based Cellular Lattice Structure Manufactured by 3D Printing

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**Abstract:** Additive manufacturing (AM) has a greater potential to construct lighter parts, having complex geometries with no additional cost, by embedding cellular lattice structures within an object. The geometry of lattice structure can be engineered to achieve improved strength and extra level of performance with the advantage of consuming less material and energy. This paper provides a systematic experimental evaluation of a series of cellular lattice structures, embedded within a cylindrical specimen and constructed according to terms and requirements of ASTM D1621-16, which is standard for the compressive properties of rigid cellular plastics. The modeling of test specimens is based on function representation (FRep) and constructed by fused deposition modeling (FDM) technology. Two different test series, each having eleven test specimens of different parameters, are printed along with their replicates of 70% and 100% infill density. Test specimens are subjected to uniaxial compressive load to produce 13% deformation to the height of the specimen. Comparison of results reveals that specimens, having cellular lattice structure and printed with 70% infill density, exhibit greater strength and improvement in strength to mass ratio, as compared to the solid printed specimen without structure.

**Keywords:** additive manufacturing; function representation; cellular lattice structure; compressive testing; strength to mass ratio



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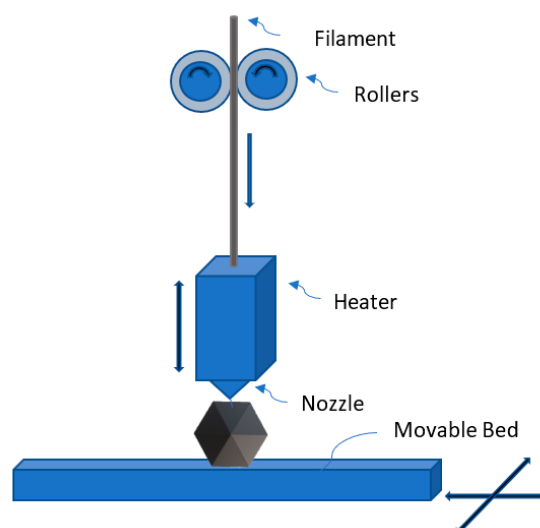
## 1. Introduction

Additive manufacturing (AM), mostly referred to as 3D printing, is known as the family of processes used to manufacture parts by accumulating thin layers of material over the previously deposited one. The pattern of deposition follows 3D CAD data available through slicing of a digital model. Each layer is deposited on x-y plane, whereas layer upon layer deposition in z direction determines the height of the 3D printed object. Application areas of AM are automotive sector [1], aerospace applications [2], marine, oil and gas sector, heavy machinery, consumer sector [3], biomedical field [4], architectural miniature models, civil construction works [5,6], food industry [7], and repair works of degraded parts [8]. The variety in AM processes is created by processes designed to use a variety of materials, at different physical conditions, and during the time of manufacture [9].

In 1991, three AM commercial machines, based on unlike processes, were introduced: Fused Deposition Modeling (FDM) by Stratasys, Solid Ground Curing (SGC) by Cubital, and Laminated object manufacturing (LOM) by Helisys [10]. Among all of the AM machines, FDM is third in top of the line machines, for its characteristics of producing functional parts of complex geometry, using various thermoplastic materials safely within a closed environment [11].

FDM process involves a layer-by-layer deposition of material extruded through a nozzle. During extrusion, the nozzle is following a predefined path, created according to the geometry of each layer. The commonly used material is plastic or wax, supplied in the form of filament, heated through heating coils. Heating coils are attached to the

nozzle such that the material can be maintained at  $0.5^{\circ}\text{C}$  above the melting temperature before extrusion. Extruded material fuse and solidify immediately over the previously deposited layer. Thus, a layer-by-layer deposition of material is carried out on a heated platform, which allows minimum distortion in part. After completion of a single layer, space is provided according to the diameter of the nozzle for the next layer, as shown in Figure 1.



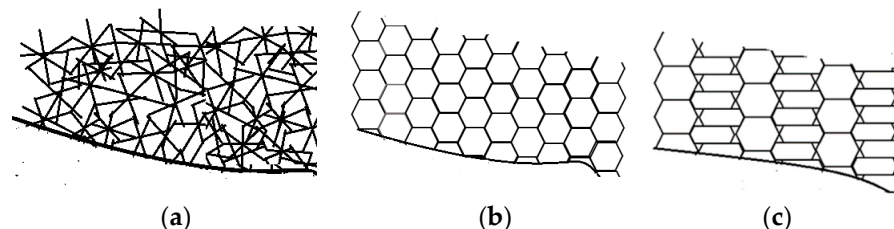
**Figure 1.** Process Schematic diagram for FDM Process.

During slicing operation for FDM printing, supports are added to eliminate risk of collapsing the material at areas, freely hanging and extending outwards, beyond the main geometry of the model. Break away type of support structures can be easily removed after the completion of the building process [12]. Along with the support structure, infill material is specified during slicing operation. Infill is the amount of material used to fill inside the cavity of the model, specified, in percentage, of cross sectional areas, ranging from 100% infill to 0% infill material to build the model [13].

Cellular structures are ordered materials that are constructed by the repetition of a unit cell [14]. The promising properties of these materials are their lightweight construction, higher strength and energy absorption with minimum material consumption. The principles that drive the properties of cellular solids depends on the material, the joining pattern of cell through the edge, face, or vertices, and the relative density of the structure [15–17]. Cellular structures can be segregated as natural occurring or artificially produced by humans, which include structures made up of cells with open or closed boundaries, randomly distributed or periodic, and 2D or 3D in structure [11]. Nature has provided an unlimited variety of these structures around and within us. Most common naturally occurring cellular structures are wood [17], bone structure [18], corals and cork [15], toucan beak [19], and many more. Humans get the inspiration from the variety of design and use of these structures, by nature, and adopt them in their construction.

Lattice structure, initially defined by Gibson and Ashby as three dimensional cellular structure having cell walls, follows random orientation in space [15]. Although initially defined, many researchers do have their own understandings for lattice structure, based upon the definition by Gibson and Ashby, as lattice structure does not rely completely on the dimensions and connecting style of the struts and nodes. In general, lattice structure is defined as being composed of interconnected cells, arranged in a repeated manner, to build a three dimensional structure, whereas the cells are an assembly of struts and nodes [20–23]. Based upon the placement pattern of unit cells in three dimensional Euclidean space, lattice structures are divided into three categories [24]:

1. Disordered lattice structure: The distribution of unit cells within the defined space do not follow any pattern, and is arbitrary and unplanned, as shown by Figure 2a.
2. Periodic lattice structure: Here, the distribution of unit cells is repeated periodically, having the same topology, geometry, and size, as shown in Figure 2b.
3. Pseudo-periodic lattice structure: Also known as conformal lattice structure, as depicted in Figure 2c, each unit cell holds the same topology with variations in shape and size.



**Figure 2.** Categorization of lattice structure: (a) Disordered lattice structure; (b) Periodic lattice structure; (c) Pseudo-periodic lattice structure.

Modeling of cellular lattice structure depends on traditional approaches related to surfaces: boundary representation and voxels (discrete volume representation). It is observed that these approaches are successful, up to some extent, and limited by design complexities of regular cellular lattice structure. The problems intensify further when modeling irregular cellular lattice structure. For such cases, each representation requires time to render the object and larger processing power, which mostly exceeds the processing power of computing machines. Qualitative problems are related to precision, operability, and manufacturability. Surface generated through boundary and voxel representation are problematic to manufacture due to defects (cracks, self-intersection, false and residual polygons) created during modeling, which produces an approximate instead of an exact geometry. Both representations are not supported for parametrization. If parameters are changed, the user needs to regenerate using a high-level procedure [25]. Most of the associated problems of the traditional approach to modeling, as stated above, are addressed by the function-based approach. Some recent research claims that implicit functions are markedly suitable for porous as well, as it can successfully be used for geometric modelling of objects, including cellular lattice structure [25–28].

To investigate properties of cellular lattice structure, several different geometries of unit cells are used by researchers to construct them. Wang et al. utilized a unit truss with five strut members to generate an octet truss conformal cellular lattice structure [29,30]. A complete design and experimental analysis study were conducted by Beyer for cellular lattice structure [31]. Three different types of structures: square pyramidal, tetrahedral, and kagome sourced structure are produced and tested for compressive and flexural strengths. The experimental results were analyzed and compared with the corresponding strengths of the solid structure, which shows the strengths are close to the solid structure. The research findings from Beyer triggered researchers to investigate the potential of truss lattice structures and surface network structures, in compression, to extend their application areas. The study performed by Jansson et al. compares network structures based on truss-lattices and periodic surfaces. The structures were designed and analyzed by Finite element software Abaqus, and the findings show the periodic surface networks are much stiffer than truss lattice structures [32]. Several lattice structures are generated through periodic octet cell, including Octet, Cross, FrameCross, InsideCross, and OctetFramed to measure their performance in compression [21]. Experimental study, by Ravari et al. and Lyibilgin et al. [33,34], was conducted to investigate the mechanical properties of variety of different cellular lattice structures including circle, square, triangle, diamond, honeycomb, and BCCZ manufactured through FDM process. Kagome lattice structure was investigated by Gautum et al., whose study reveals that build orientation and printing imperfections have considerable effects on mechanical properties of the structure [35].

The acceptance of cellular lattice structure directly relates to the advancements and capabilities of AM processes to create design complexities without increasing manufacturing cost. Hence, it improves the feasibility to manufacture graded parts [14]. Through design complexities of cellular lattice structure, some of the properties of these structures can be influenced directly. An adjustment in topology and dimensions of the cell geometry of structure can lead to a physical retort of these structures to display properties unattainable by their base material [36], including mechanical, acoustic, and dielectric properties [37–39]. The higher strength to weight ratio, and structure thermal conductivity, makes lattice structures a suitable option for aerospace industry [40]. According to the details mentioned above, objects made up of cellular lattice structure provides the benefits of reduction in weight, material, larger surface area to volume ratio, and, for some particular AM processes, less time and energy requirements. It is therefore predicted that most digital fabricated solid objects will be constructed via cellular lattice structures in future [25].

Although it seems that a variety of unit cell types are used to generate cellular lattice structures, a detailed study, performed by Helou and Kara [41], highlights that unit cell types used in previous published research are very limited, around 40 in number, and not all of them are of new design. Some of them are derived from basic existing unit cell type. There exists an immediate requirement of innovative design of cellular lattice structures to be used for different situations and applications. An in-depth survey reveals that none of the researchers, used to generate series of lattice structures, investigated their mechanical performance in compression. We have taken this requirement as our main target of study, which involves design, construction, and investigation of the behavior of lattice structures. This study presented an innovative approach to optimize the use of infill material at the inner region by assigning values to percentage of infill material, frequency, and vertical shift, which determines the thickness and the distance between the bars of the cellular lattice structure. Function based approach is applied to the design and modeling of the series of cellular lattice structure, and performance of each member of series is determined through experimental investigation. The organization of the manuscript is according to the sequence of activities for study. Section 2 provides methodology and the information related to material, machines, process parameters, standard to follow, and modeling requirements of cellular lattice structure. Modeling details of a series of cellular lattice structures is discussed in Section 3. Section 4 provides details of the results of experimental evaluation, and finally, in Section 5, the results and findings are discussed. Section 6 provides the conclusion of the study.

## 2. Methodology

This section deals with step by step procedure, in detail, to design a series of internally built-in cellular lattice structure within objects of closed boundaries, such that each object contains a unique internal structure, with dimensions of details orders of magnitude lesser than the overall size of the object.

The concepts applied in this study are simple, and a basic knowledge of solid mechanics is needed for the calculations. The compressive strength ( $\sigma_c$ ) will be calculated by dividing the compressive load ( $F_c$ ) applied on the specimen by an initial cross sectional area of the specimen ( $A_{X-sectional}$ ). The strength to mass ratio will be calculated through Equation (1).

$$\text{Strength to mass ratio} = \sigma_c / M_s \quad (1)$$

where  $M_s$  is the measured mass of the specimen.

### 2.1. Material

Acrylonitrile Butadiene Styrene (ABS) and Poly-lactic Acid (PLA) are the most commonly used materials in 3D printing for functional requirements. Most of the published research investigations considered ABS either for investigation or a printing test specimen [42–46]. For our research investigation, we are using PLA Filament from Anet PLA 3D printing filament for 3D printers for the main structure, support structures, and infill

structures. The material is used as received. The properties of the material [47–49] are shown in Table 1.

**Table 1.** Mechanical properties of PLA.

| PLA Properties                   | Value | Units             |
|----------------------------------|-------|-------------------|
| Density                          | 1.24  | g/cm <sup>3</sup> |
| Compressive Strength (Peak, STD) | 17.9  | MPa               |
| Young Modulus                    | 3.5   | GPa               |

## 2.2. Printer and Parameters

Prusa i3, an open-source 3D printer, is used for printing test specimens. The selected printing parameters are given in Table 2.

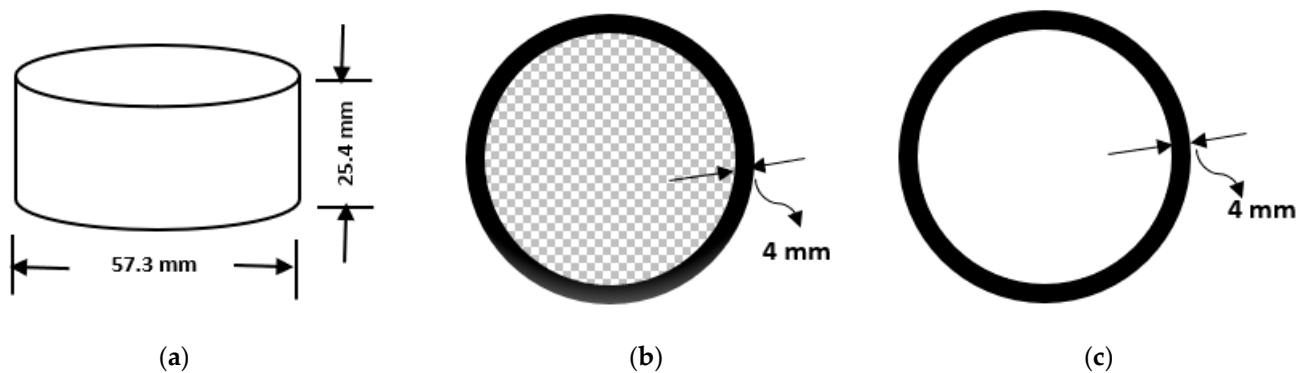
**Table 2.** Printing Parameters of 3D Printer.

| Printing Parameter | Value | Units |
|--------------------|-------|-------|
| Filament diameter  | 1.75  | mm    |
| Nozzle Diameter    | 0.4   | mm    |
| Print Temperature  | 210   | °C    |
| Bed Temperature    | 50    | °C    |
| Layer Height       | 0.2   | mm    |
| Print Speed        | 50    | mm/s  |
| Travel Speed       | 150   | mm/s  |

## 2.3. Testing Procedure

Tinius Olsen Hydraulic Universal Testing Machine (300SL) is used for the execution of the experimental tests which meets ASTM E4, BS 1610, DIN 51221, EN 10002-2, and ISO 7500-1 standard. The machine is equipped with two hardened steel plates, both parallel to each other in a plane, perpendicular to the axis of the test specimen. The test specimen is loaded between the plates, ensuring that the outer surface of the specimen is parallel to the compression plates. The compression speed for test is adjusted as 2.5 mm/min, keeping it uniform from start of the compression until it reaches a strain level equal to 16% of its original length, as in the ASTM standard document. During testing, magnitude of uniaxial compressive load and percent reduction in height are recorded for further use in calculations.

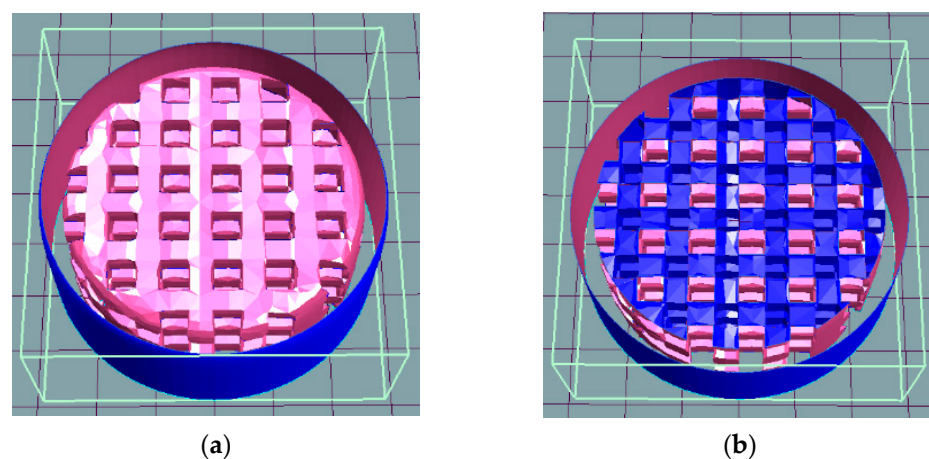
The test specimens are manufactured and tested according to “Standard test method for compressive properties of rigid cellular plastics” (ASTMD1621-16). Each test specimen for the study is around a closed cylindrical shell except the base, the diameter and height are calculated and kept at 57.3 mm and 25.4 mm, respectively, as shown in Figure 3a. With respect to the internal geometry, there are two different types of specimen, with one having cellular lattice structure inside the cylindrical shell, as shown in Figure 3b. The details of the geometry and dimensions of cellular lattice structure are presented in Section 3. The second type of specimen is a hollow cylindrical shell (will be called “solid part”), as shown by Figure 3c. The base of both type of specimen are not closed and the shell has a uniform wall thickness of 4 mm, as shown by Figure 3b,c. After printing, the masses of each specimen are calculated and measured through a digital scale, with readability up to 0.0001 g (0.1 mg). The masses of the specimen are mentioned in Section 4. The observed variations in calculated and measured masses were found to be less than 2% in all test specimens. For the study, we use the measured values of the masses.



**Figure 3.** Dimensions of test specimen (a) Test specimen overall dimensions (b) X-sectional view of test specimen with internal cellular lattice structure (c) X-sectional view of hollow test specimen (solid part).

### 3. Modeling of Cellular Lattice Structure

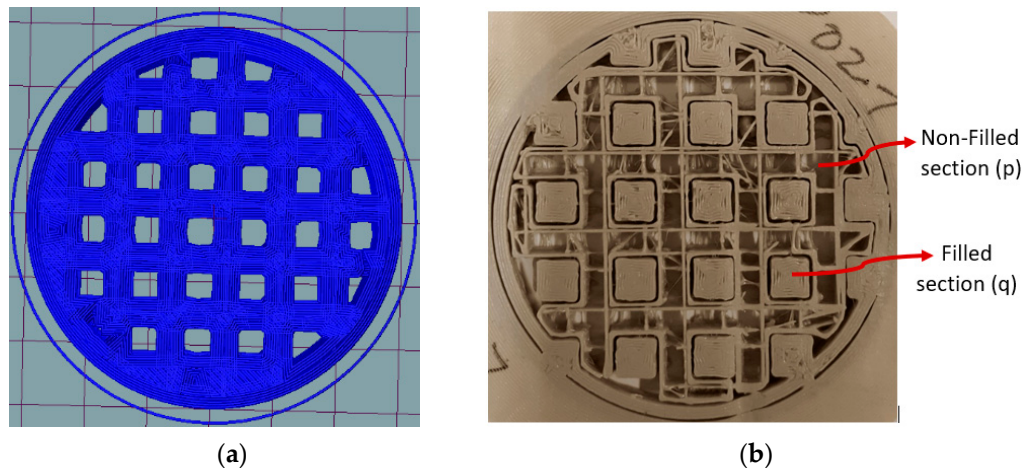
As discussed, use of  $R$  functions are more efficient than boundary representation and voxel based modeling techniques. We propose to construct a series of objects having unique cellular lattice structure inside and within the closed boundaries, using trigonometric functions and  $R$ -functions. For working with function representation, “HyperFun, a modeling language”, a simple specialized high level programming language and associated software, designed to set out function based models, is used [50]. To construct the series of cellular lattice structure within a closed cylinder, an algorithm is developed and given at the end of the section. The series is constructed by assigning values to variables, *frequency* ( $f$ ) and *vertical shift* ( $v$ ) used in sin function. The values of frequency are taken, which are 19 ( $f_1$ ) and 21 ( $f_2$ ), whereas the vertical shift is varied from “0” to “0.4” with an increment of “0.1”. Frequency controls the length of the period, and vertical shift controls the division within a period. The selected values of frequency and vertical shift are according to the size limitations of test specimen following the standard ASTM D1621-16 and printing capabilities of 3D printing machine. The internal lattice structure consists of intersecting vertical and horizontal hollow bars, generated through function representation, as shown in Figure 4a. Figure 4b provides the x-sectional view of the specimen through the bars to show the hollow regions of the bar.



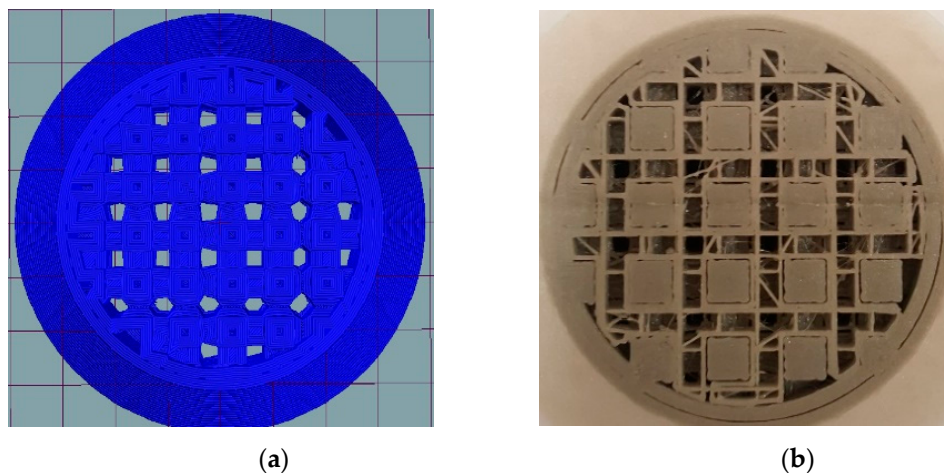
**Figure 4.** X-sectional views of test specimen with (a) complete lattice structure within the shell (b) internal structure of the hollow bar.

During printing, material accumulates to form the outer surfaces of the hollow bar, and the same material (PLA) accumulates in the space between the hollow bars to form intersecting vertical and horizontal column-like structure (solid bar). Some extra material is

consumed to act as support material and provide support to hollow bars. Figures 5 and 6 show the internal structure of a test specimen after rendering plus slicing and printing operations. The variation in the thickness of the hollow bars and material distribution for the same frequency and different values of vertical shift can be seen by comparing Figure 5a with Figures 6a and 5b with Figure 6b, respectively.



**Figure 5.** X-sectional top views of test specimen with frequency “19” and vertical shift “0” (a) after rendering plus slicing (b) after printing.



**Figure 6.** X-sectional top views of test specimen with frequency “19” and vertical shift “0.4” (a) after rendering plus slicing (b) after printing.

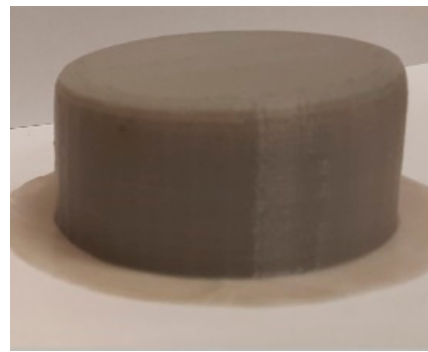
The outer shape, inside structure, and geometry of the rendered and printed test specimen is shown in Figure 7a–c, respectively. Figure 7b shows the magnified view of the internal structure containing the dimensions after rendering. Here, “p” is the thickness of the hollow bar and “q” is the distance between the hollow bars, which is empty space. The empty space between the hollow bars, shown in Figure 7b, is then filled by the same material (PLA) during printing, as shown by Figure 7c, to form solid bars. Tables 3 and 4 show dimensions “p” and “q” in millimeters related to each specific test specimen.

**Table 3.** Thickness of hollow bars (non-filled sections) in millimeters (p).

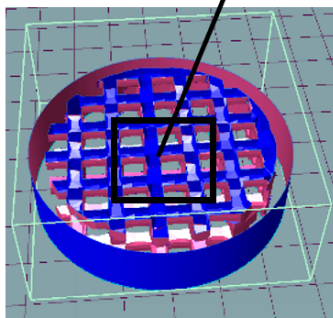
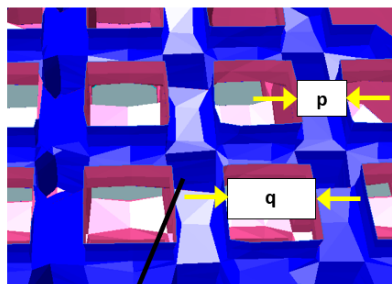
| Frequency (f) |    | Vertical Shift (v) |     |     |     |     |
|---------------|----|--------------------|-----|-----|-----|-----|
|               |    | 0                  | 0.1 | 0.2 | 0.3 | 0.4 |
| $f_1$         | 19 | 4.2                | 4.5 | 4.8 | 5.3 | 5.3 |
| $f_2$         | 21 | 3.8                | 4.3 | 4.5 | 4.9 | 4.9 |

**Table 4.** Distance between bars (filled sections with 3D printed material) in millimeters ( $q$ ).

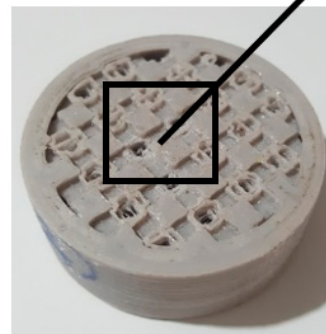
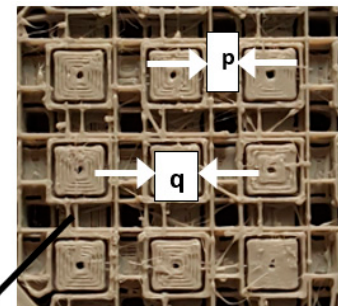
| Frequency ( $f$ ) |    | Vertical Shift ( $v$ ) |     |     |     |     |
|-------------------|----|------------------------|-----|-----|-----|-----|
|                   |    | 0                      | 0.1 | 0.2 | 0.3 | 0.4 |
| $f_1$             | 19 | 4.2                    | 3.9 | 3.6 | 3.3 | 3.1 |
| $f_2$             | 21 | 3.8                    | 3.3 | 3.1 | 2.9 | 2.7 |



(a)



(b)



(c)

**Figure 7.** External and Internal geometry (a) Outer shape of the specimen after printing (b) X-sectional view, illustrating internal structure of the test specimen and related dimensions after rendering (c) X-sectional view illustrating internal structure of the test specimen and related dimensions after printing.

The Algorithm 1, presented below is used to construct ten unique compressive strength test specimens with built in cellular lattice structure by altering values of frequency ( $f$ ) and vertical shift ( $v$ ). According to the standard, five replicates should be constructed and tested for each type of specimen, but due to time constraints, three replicates are made and tested [51]. Average values of test results are considered for evaluation. Test specimens are constructed with 100% and 70% infill density, tested, and their results are compared with specimen of same infill density without internal structure (solid part). All the specimens are printed through Prusa i3, an open source 3D printer, keeping x-y plane of specimens parallel to the print bed. Top and bottom surfaces of specimens are made parallel after

printing, and their dimensions are kept, according to ASTM 1621-16. The X-sectional views of specimens after rendering are presented in Table 5.

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**Algorithm 1** Construction of a cellular lattice structure within closed cylindrical object

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**Procedure:** regular( $x, y, z$ )

Construct slabs orthometric to ( $x, y, z$ ) axes:

$$s_x = \sin f(x) + v(x)$$

$$s_y = \sin f(y) + v(y)$$

$$s_z = \sin f(z) + v(z)$$

Construction of the bars by intersection operation:

$$b_x = s_y \wedge s_z$$

$$b_y = s_x \wedge s_z$$

$$b_z = s_x \wedge s_y$$

Perform blending union operation over the constructed bars:

$$\text{blend1} = hfBlendUni(b_x, b_y, 1, 0.2, 0.2)$$

$$\text{blend2} = hfBlendUni(b_x, b_z, 1, 0.2, 0.2)$$

$$\text{blend3} = hfBlendUni(b_y, b_z, 1, 0.2, 0.2)$$

Construction of infinite lattice structure by union operation:

$$\text{regularlatticestructure} = rls.$$

$$rls = \text{blend1} \vee \text{blend2} \vee \text{blend3}$$

Construction of closed cylindrical shell:

$$\text{cylinder}_1 = cl_1 = 1.3 - x^2 - y^2$$

$$\text{plane}_1 = pl_1 = 0.40 - z$$

$$\text{closedcylinder}_1 = (ccl_1)$$

$$ccl_1 = hfblendInt(cl_1, pl_1, -0.1, 0.1, 0.1)$$

$$\text{cylinder}_2 = cl_2 = (1.3 - x^2 - y^2) - 0.3$$

$$\text{plane}_2 = pl_2 = 0.32 - z$$

$$\text{closedcylinder}_2 = (ccl_2)$$

$$ccl_2 = hfblendInt(cl_2, pl_2, -0.1, 0.1, 0.1)$$

$$\text{closedcylindricalshell} = ccs$$

$$ccs = ccl_1 \setminus ccl_2$$

Insertion of lattice structure within closed cylindrical shell:

$$\text{trimmedregularlatticestructure} = trls.$$

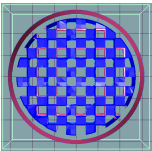
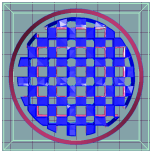
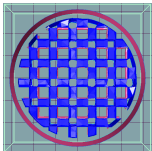
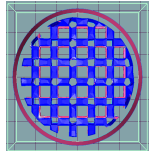
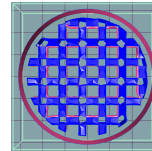
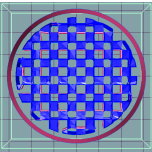
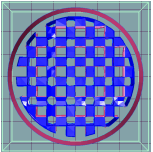
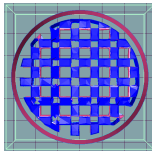
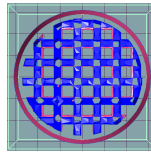
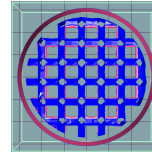
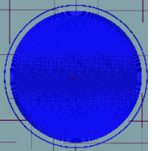
$$trls = hfblendInt(ccl_2, rls, 0.1, 0.1, 0.1).$$

$$\text{result} = hfBlendUni(ccs, trls, 0.1, 0.1, 0.1)$$

**return:** result.

---

**Table 5.** X-sectional views of the test specimens constructed through Algorithm 1, given above.

| Type                       | Frequency ( $f$ ) | Vertical Shift ( $v$ )                                                               |                                                                                     |                                                                                      |                                                                                       |                                                                                       |
|----------------------------|-------------------|--------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|                            |                   | 0                                                                                    | 0.1                                                                                 | 0.2                                                                                  | 0.3                                                                                   | 0.4                                                                                   |
| Cellular Lattice Structure | $f_1$ 19          |   |  |  |  |  |
|                            | $f_2$ 21          |   |  |  |  |  |
| Solid Part                 | S -               |  |                                                                                     |                                                                                      |                                                                                       |                                                                                       |

#### 4. Testing of Built-In Cellular Lattice Structure

##### 4.1. First Test Series

The first test series of eleven test specimens are constructed with 100% infill density. Out of eleven, ten unique test specimens, having internal structure within them, are constructed, and one solid test specimen is constructed as indicated in Table 5. The specimens are constructed with 100% infill density by using the regular infill pattern provided by the software Repetier-Host. Three replicates of each test specimen are made and tested. Tables 6 and 7 show the data summary of the characteristics and results of the first test series.

**Table 6.** First test series results of test specimens with frequency 19 and 100% infill density.

| Type                       | $f_1$ | $v$ | Average Mass of Specimen (g) | Average Compressive Load ( $F_c$ ) (kN) | Strength/Mass Ratio (MPa/g) |
|----------------------------|-------|-----|------------------------------|-----------------------------------------|-----------------------------|
| Cellular Lattice Structure | 19    | 0   | 61.7                         | 105                                     | 0.68                        |
|                            | 19    | 0.1 | 62.3                         | 107                                     | 0.67                        |
|                            | 19    | 0.2 | 60.7                         | 113                                     | 0.71                        |
|                            | 19    | 0.3 | 63.7                         | 118                                     | 0.71                        |
|                            | 19    | 0.4 | 63.2                         | 117                                     | 0.7                         |
| Solid Part                 | -     | -   | 82.7                         | 169                                     | 0.78                        |

**Table 7.** First test series results of test specimens with frequency 21 and 100% infill density.

| Type                       | $f_2$ | $v$ | Average Mass of Specimen (g) | Average Compressive Load ( $F_c$ ) (kN) | Strength/Mass Ratio (MPa/g) |
|----------------------------|-------|-----|------------------------------|-----------------------------------------|-----------------------------|
| Cellular Lattice Structure | 21    | 0   | 62.65                        | 90                                      | 0.59                        |
|                            | 21    | 0.1 | 62.3                         | 107                                     | 0.67                        |
|                            | 21    | 0.2 | 61.5                         | 106                                     | 0.66                        |
|                            | 21    | 0.3 | 62.9                         | 115                                     | 0.7                         |
|                            | 21    | 0.4 | 65.4                         | 132                                     | 0.78                        |
| Solid Part                 | -     | -   | 82.7                         | 169                                     | 0.78                        |

##### 4.2. Second Test Series

The second test series, of eleven test specimens, are constructed with 70% infill density. Out of eleven, ten unique test specimens, having internal structure within them, are constructed, and one solid test specimen is constructed as indicated in Table 5. The specimens are constructed with 70% infill density by using the regular infill pattern provided by the software Repetier-Host. Three replicates of each test specimen are made and tested. Tables 8 and 9 show the data summary of the characteristics and results of the second test series.

**Table 8.** Second test series results of test specimens with frequency 19 and 70% infill density.

| Type                       | $f_1$ | $v$ | Average Mass of Specimen (g) | Average Compressive Load ( $F_c$ ) (kN) | Strength/Mass Ratio (MPa/g) | % Improvement in Strength/Mass Ratio |
|----------------------------|-------|-----|------------------------------|-----------------------------------------|-----------------------------|--------------------------------------|
| Cellular Lattice Structure | 19    | 0   | 59.5                         | 78                                      | 0.50                        | 31.5                                 |
|                            | 19    | 0.1 | 61.1                         | 76                                      | 0.48                        | 26.3                                 |
|                            | 19    | 0.2 | 59.9                         | 76                                      | 0.49                        | 28.9                                 |
|                            | 19    | 0.3 | 60.7                         | 90                                      | 0.57                        | 50.0                                 |
|                            | 19    | 0.4 | 59.98                        | 92                                      | 0.59                        | 55.2                                 |
| Solid Part                 | -     | -   | 62.4                         | 62                                      | 0.38                        | -                                    |

**Table 9.** Second test series results of test specimens with frequency 21 and 70% infill density.

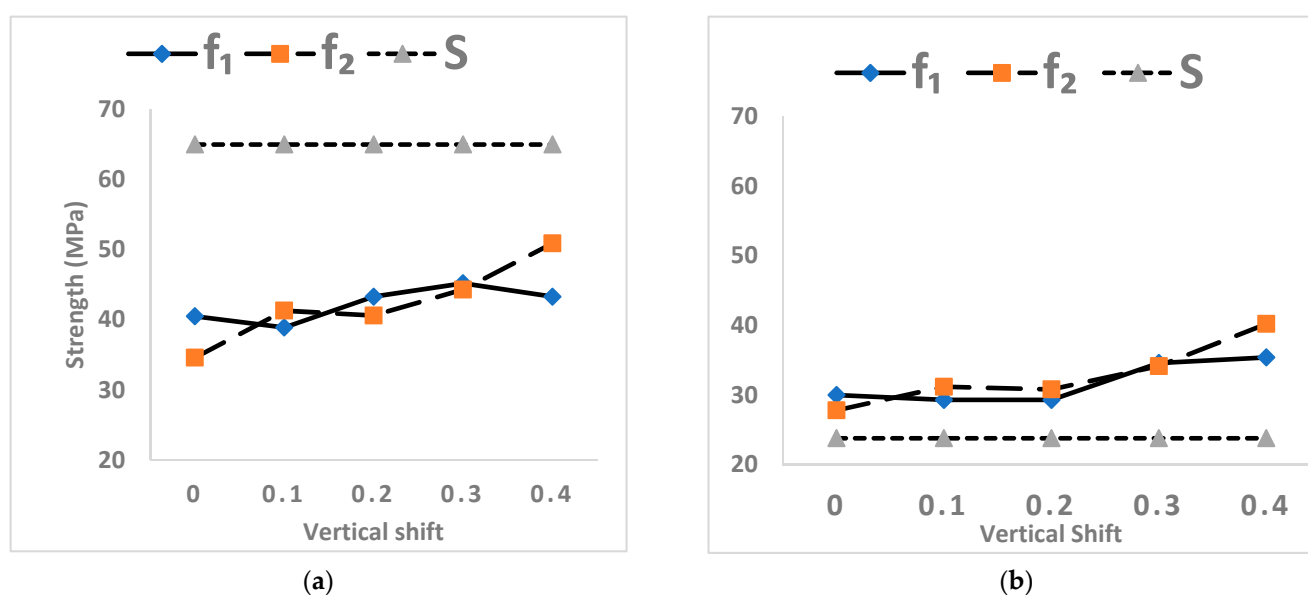
| Type                       | $f_2$ | $v$ | Average Mass of Specimen (g) | Average Compressive Load ( $F_c$ ) (kN) | Strength/Mass Ratio (MPa/g) | % Improvement in Strength/Mass Ratio |
|----------------------------|-------|-----|------------------------------|-----------------------------------------|-----------------------------|--------------------------------------|
| Cellular Lattice Structure | 21    | 0   | 58.4                         | 72                                      | 0.47                        | 23.6                                 |
|                            | 21    | 0.1 | 61                           | 81                                      | 0.51                        | 34.2                                 |
|                            | 21    | 0.2 | 61.2                         | 80                                      | 0.5                         | 31.5                                 |
|                            | 21    | 0.3 | 60.17                        | 89                                      | 0.56                        | 47.3                                 |
|                            | 21    | 0.4 | 62.72                        | 105                                     | 0.64                        | 68.4                                 |
| Solid Part                 | -     | -   | 62.4                         | 62                                      | 0.38                        | -                                    |

## 5. Results and Discussion

Testing of series 1 and series 2 specimens was carried out as described in Section 3. We have not shown the raw data due to its high volume, including around one thousand points per specimen. In this section, we will discuss the method used to convert the data into useful information.

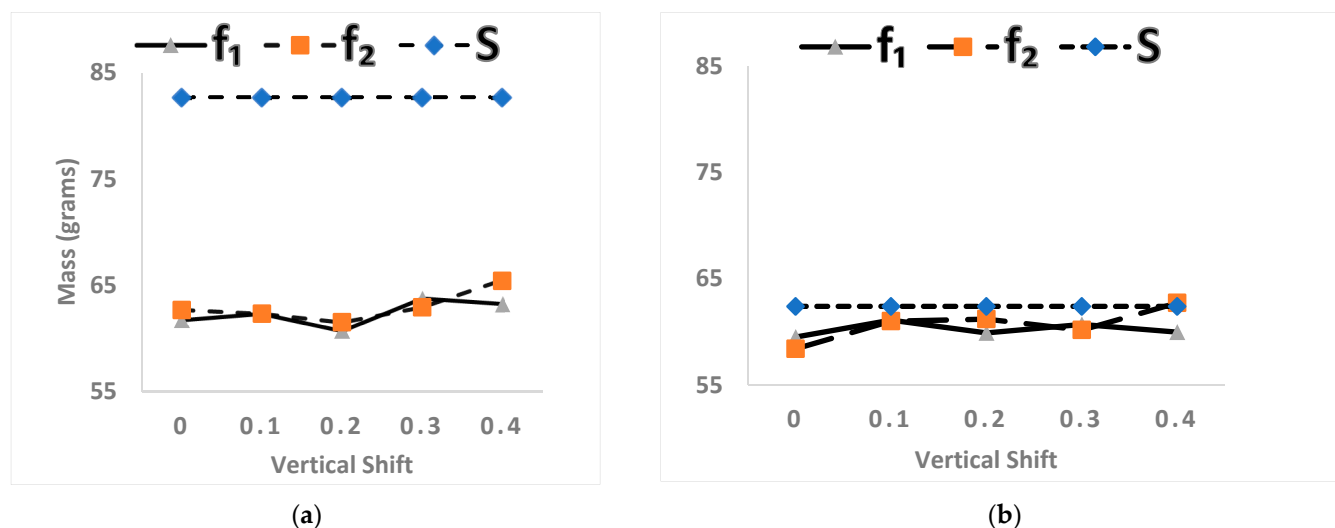
Our objective in the study is to determine the compressive strength of the structures, for which the load required to produce 13% deformation in the height of the test specimen, is applied through a testing machine (Tinius Olsen). Once the data is received from the testing machine, it is imported to an excel sheet to record the amount of load and the subsequent deformation in the test specimen. The recorded data is used to determine the compressive strength and strength to mass ratios are calculated through Equation (1). From the load and subsequent deflection, data is used to calculate the amount of strength exhibited by the specimen against 13% axial deformation.

Figure 8a,b provides the graphical representation of the data points. An increasing trend in strength is observed for both 70% and 100% infill density specimens. Figure 8a provides the comparison, which shows that the solid specimen is much stronger, as compared to the specimen having an internal structure with 100% infill density. The performance of specimens with 70% infill density (see Figure 8b) is more valued, as all of the specimen are of greater strength than the solid specimen having a 70% infill density.



**Figure 8.** Graphical representation of the relationship between strength versus vertical shift (a) with 100% infill density (b) with 70% infill density.

Figure 9a,b shows the relationship between specimen mass and vertical shift. Comparison between Figures 8a and 9a show that, for 100% infill density, the strength of specimen mostly follows the same trend, where an increase in mass increases the strength of specimen. It is also observed that, with an increase in the value of vertical shift, the mass and the strength of the specimen mostly increases.



**Figure 9.** Graphical representation of the relationship between mass versus vertical shift (a) with 100% infill density (b) with 70% infill density.

The response of the 70% infill density specimen shows better performance, as indicated by Figure 9b. Graphical representation of mass vs vertical shift shows that the masses of specimens with internal structure are equal to, or less than, the mass of solid specimen. A comparison between Figures 8b and 9b reveals that the mass of specimen is not the only factor that contributes towards greater strength, as it can be seen that specimens of equal masses do not perform uniformly and have different values of strength.

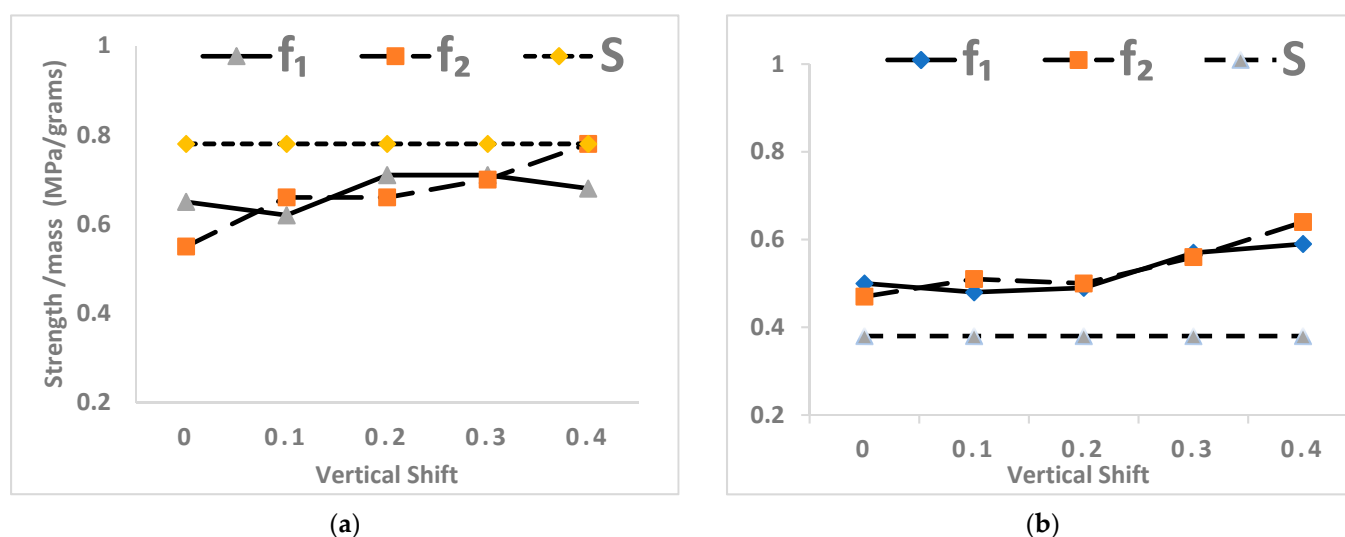
Figure 10a,b shows the strength to mass ratios versus vertical shift of specimens with 70% and 100% infill density. For 100% infill density specimens, a zigzag trend is observed for specimens with frequency  $f_1$  (19), and an increasing trend is observed for specimens with frequency  $f_2$  (21). The strength to mass ratio of solid specimens is higher than the values of 100% infill density with internal structure specimens, except for the specimen with frequency 21 and vertical shift 0.4, having the same value of strength to mass ratio. Similar results are observed through the research study of Beyer et al. [31] where the Kagome type of lattice structure performance in compression is equal, in magnitude, to the solid specimen. The performance of specimens with 70% infill density is highly regarded, including all the observations greater than the strength to mass ratio of solid specimens. A continuously increasing trend is observed for both frequencies.

Results of the second test series are more recognized, as the performance of each specimen of this series is much better than the solid specimen with 70% infill density, as shown in Tables 8 and 9. From the graphical representations in Figures 9 and 10, it can be seen that, for minor increases in values of specimen mass, the range of improvement in strength to mass ratio in comparison to solid specimen, is from 23.6% (min.) to 68.4% (max.). It is also observed that mass of the specimens range from 58.4 g to 62.72 g, and their performances are in the range of 27.8 MPa to 40.2 MPa i.e., for an improvement of 7.4% in material, their performance is 44.6% better than the specimen with the least values. For the first series, these values are with a 7.7% increase in material and a 17.5% increase in strength is achieved.

Performance in the second series is further investigated and evaluated according to material distribution within the sample. Figures 8 and 9 show that the amount of

material utilized for the construction of specimens is, approximately, the same, but their strength to mass ratios are different and greater than the minor difference in their masses, if any. Comparing the values of strength to mass ratio show that higher values relate to frequency 21, and the material distribution in higher frequency specimens is more widened in the case of 70% in contrast to 100% specimens (refer to Tables 3 and 4).

The thickness of solid bars is lesser for frequency 21 and compared to frequency 19 and, for such situations with the same masses of specimen, the much expanded material distribution of specimens with frequency 21 is justified. The solid bars serve as pillars internally and provide supports to the whole geometry. For these reasons, a greater level of compressive strength is achieved when comparison is made between 70% infill solid part and 70% infill cellular lattice structure specimens. The above research findings are supported through previous published research works by Chunze et al. [37,52]. Using Direct Metal Laser Sintering process (DMLS), similar observations are made when the unit cell sizes of the cellular lattice structure are reduced to 3 mm, 5 mm, and 7 mm, respectively, within the same volume fraction. With the reduction in the cell size, sizes of struts also decrease, and during manufacturing, the thinner struts cool down much rapidly, leading to finer microstructure and stronger struts. Therefore, as the dimensions of the struts reduce, improvement is observed in the strength and mechanical properties of the cellular lattice structure.



**Figure 10.** Graphical representation of the relationship between strength to mass ratio versus vertical shift (a) with 100% infill density (b) with 70% infill density.

## 6. Conclusions

The research study has investigated the compressive strength of cellular lattice structure of two different test series manufactured by FDM technology. Comparisons of the results are made according to strength to mass ratio, compressive strength, and mass/density of the specimen.

The comparison among the 100% infill density specimen (solid specimen versus specimen with internal structure) shows that the solid specimen is much stronger, as it consumes more material. Samples of 100% infill density, with internal structure, perform much better than specimens with 70% infill density, which is evident from the data of specimens with frequency 21 and vertical shift of 0.4, printed with 100% and 70% infill density. Data of 100% infill specimen shows that, for a 4.2% increase in material, the strength rises to 26.6% higher than 70% infill specimen. Comparison within 70% infill specimen strength data suggests the use of specimens having internal structure instead of solid structure. These specimens show a balanced compressive strength property along with the benefit of material savings.

The study also shows that infill density, along with the pattern of material distribution, plays an important role for improvement in compressive strength. The results of the study can be successfully applied, according to compressive strength requirements, to different regions of objects under compression.

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