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COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION OF VIBRATION CHARACTERISTICS OF VARIABLE UNIT-CELL GYROID STRUCTURES

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ABSTRACT

Triply periodic minimal surface (TPMS) based geometries exhibit extraordinary mechanical, thermal, electrical and acoustic properties thanks to their unique topologies. There are various types of structures in the TPMS family. One of the most well-known TPMS structures is the gyroid structure. This paper focuses on the vibrational behavior of a novel sandwiched gyroid structure in terms of their natural frequencies and mode shapes with three different feasible unit sizes at same volume ratio. Powder bed fusion technology is employed to fabricate gyroid porous specimens made of HS188 material. Modal testing is performed to deduce the vibration characteristics of aforementioned cellular structures. Besides the experimental study, the dynamic performance of the considered structures is investigated computationally by performing modal analysis using Finite Element (FE) models. A key challenge facing FE modelling of large scale gyroid structure is computation time and accuracy. For that reason, small size of gyroid lattices are utilized for compression tests in order to extract elastic properties. Then sandwiched gyroid plate is modelled as solid body with calculated elastic properties instead of complex gyroid topology and analyzed. Finally correlation level between experimental and FE results are presented.

1 INTRODUCTION

Additive manufacturing (AM) is a type of a manufacturing process, where material is added layer-by-layer in contrast to the traditional methods in order to create the end product. AM has gained great attention from industry since it reduces the design restrictions associated with the conventional manufacturing methods. This method allows the manufacturing of complex free-form geometries providing high mechanical properties with lower weight and superior functional characteristics. The essence of all AM processes is the generation of each layer by slicing the Computer Aided Design (CAD) data. The AM system utilizes the aforementioned data to create the end product layer-by-layer with suitable techniques according to the selected material. For metals, there are many modalities used in the industry and many more are still under development. The selection of the correct modality plays a critical role in achieving the desired characteristics of the final products [1, 2].

Powder bed fusion systems, also as known as selective laser sintering (SLS), selective laser melting (SLM) or direct metal laser melting (DMLM), are the most widely researched AM modalities. In particular, DMLM has opened up new possibilities for creating various meta-materials. These materials possess favorable properties regardless of the chemical contents, manufacturing methods used and enhancing post-processes applied. Therefore, such materials gained the attention of aerospace, personal protective equipment and transportation industries.

In applications where the weight is critical, it is important to meet the durability requirements of the structure using minimum amount of material under operational loads. Components in such applications are, in general, subject to combined loading due to torsion, tension, and bending loadings. This requires that such design is carefully engineered in order to achieve material properties much better than that of the bulk material. To achieve this, cellular structures have long been used in many engineering applications because of their highly configurable mechanical properties together with light weights. A cellular structure is considered as the building block of the whole structure. Each of these units is called unit cells and the properties of each unit cell along with the stacking method define the mechanical properties of the whole structure [3].

A type of cellular structures, lattices, is composed of network of trusses and beams varying in size and arrangement. A study on lattices can be conducted treating them as either a complex network of trusses, beams and connections by traditional means or as meta-materials [4]. As much as lattices have their advantages, manufacturing of such structures is costly using traditional methods. With the recent advances in additive manufacturing, lattices have started to gain significant consideration. A variety of different unit cell designs have been recently investigated to further understand their mechanical properties [5, 6].

Another great enhancement that AM brings in manufacturing of lattices is the capability of changing the unit cell design parameters relative to the loading conditions and structural requirements. Due to their tunable stiffness and different truss diameters, lattice structures are also proposed and proven to have supportive functionality in additive manufacturing [7]. Effect of design parameters of lattice structures on their mechanical properties should be well understood for their further utilization in the aforementioned industries. The current state of the art in unit cell design is yet to reach its limit for efficiency. By numerical proofs, computational models and bio-mimics, there is a huge potential for inventing and implementing novel advanced unit cell designs.

Among the promising unit cell designs, periodic structure model of minimal surfaces have captured researcher’s attention. Mathematical advances especially in group theories are essentially significant for explaining and analytically modeling the repetitive occurrences observed in nature. One of the well-known periodic surface models is triply periodic minimal surface (TPMS). There are many surfaces belonging to the TPMS family in the literature. Such surfaces include Schwarz crossed layers of parallels (CLP), Diamond, Neovius, Schoen I graph and wrapped package-graph (IWP) and Fischer-Koch S models. These TPMS were characterized using different methods in the previous studies [8-10]. Utilizing additive manufacturing, TPMS models can now be manufactured in addition to their computational analysis.

As the studies on lattice structures have shifted towards surface models that can provide better properties than truss lattices, many reported using additive manufacturing for printing TPMS models and testing [11, 12]. Being a member of the large TPMS family, double gyroid (DG), which is a subtype of gyroid form, has shown to express high stiffness and low Von Misses stress compared to many other surfaces in the literature [13]. Same study also revealed that double gyroid structures also possess similar stiffness in both axes, which can be utilized in applications where direction of the stress is unknown. Another research suggests that DG lattices are a promising candidate for usage in lightweight energy absorbing applications [14]. In another study, vibration characteristics of TPMS based geometries including gyroid form were analyzed and effect of wall thickness was investigated computationally [15].

In the aforementioned studies from the literature, the mechanical characteristics of various type of TMPS forms were investigated in terms of compressive and energy absorption behaviors experimentally and numerically. In this paper, it is aimed to reveal dynamic characteristics of a novel double gyroid sandwich structure with three different unit cell sizes. Unlike finite element modelling approaches using 3D elements in the literature, in this study, a computationally efficient simulation methodology via representative models is proposed for double gyroid structure. For that purpose, small scales of gyroid samples with different unit cell sizes at same volume ratio are subjected to compression test in order to identify elastic material properties. Thereafter, calculated young modulus values are assigned to sandwiched gyroid structures in which gyroid unit cells are not modelled explicitly but as solid geometry. Finally, numerical studies are validated by experimentally for one additively manufactured gyroid sandwich structure using modal testing equipment.

The paper is organized as follows. First, we extract the elastic constants of the gyroid lattice by performing compressive tests for various unit cell sizes. Next, a static analysis performed for a cube, which directly represents gyroid test samples, in order to find correct young moduli. Verified young modulus is used to finite element modelling of a sandwiched gyroid structures. The dynamic response of considered geometry is then investigated in terms of natural frequencies and mode shapes.

2 EXPERIMENTAL METHODS

2.1 Design and Manufacturing of the Gyroid Cellular Structure for Compression Test

Computer-Aided Design (CAD) files can be designed using different approaches. For the aforementioned periodic cellular structures, instead of direct CAD modelling, unit cells are modelled by using a mathematical formula given in Eq. (1) as:

$$\left(cos(\frac{2\pi}{\alpha}x)sin(\frac{2\pi}{\alpha}y)+cos(\frac{2\pi}{a}y)sin(\frac{2\pi}{a}z)+cos(\frac{2\pi}{a}z)sin(\frac{2\pi}{a}x)\right)^2 = t^2 \tag{1}$$

where α is unit cell size and t is the thickness of DG's model.

The function is utilized for generating surface of DG structures in MATLAB platform. This approach enables the generation of continuous modelling of specimens in a computationally efficient way for the subsequent operations performed in Unigraphics (UG) 12. Once the surface representation is completed in MATLAB as shown Figure 1, geometry is exported in facet body format. Wall thickness of complex DG unit cells is then assigned in UG using solid modeling options. In this study, we used three different unit cell sizes of 6, 8, 12 mm to create 24x24x24 mm test samples at same volume ratio for compression tests. Theoretical properties of three test specimens are given in Table 1.

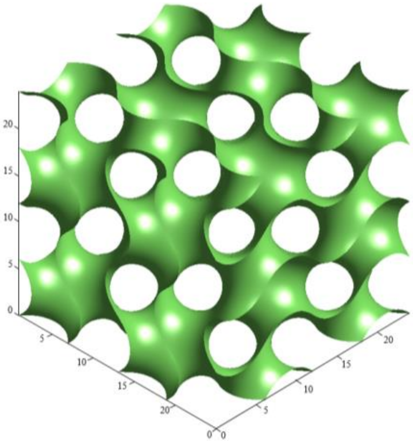


Figure 1: Surface representation in Matlab.

Table 1: Theoretical properties of the specimen

Unit cell size (mm)	thickness (mm)	Volume (mm^3)	Cell count	Volume fraction	Surface area (mm^2)
6	0.4	2829	96	0.20	14648
8	0.533	2830	27	0.20	10496
12	0.8	2830	8	0.20	7596

The finalized geometry files should be sliced prior to the printing process. Selected software generates the path that the laser will scan through during the process. Hence, sliced file mainly contains the laser scan path for each layer and layer thickness. In this study, specimens are additively manufactured in Concept Laser M2 Cusing, which is a direct metal laser melting machine containing 2 x 400 W fiber laser systems. Among the additive manufacturing modalities and hardware available, powder bed fusion is the most advanced technology. Ability to manufacture small part features with high precision, resulting solid material integrity and reduced lead times make this modality very convenient for manufacturing micro, mezzo and macro scale lattice structures. Considering the advantages of manufacturing specimens of interest as well as the powder and machine availability, direct metal laser melting system is used in the study.

Material selection is another crucial factor, which plays an important role for additive manufacturing process and directly determines the mechanical characteristics of specimens. The DG test samples are fabricated with HS188 powder with spherical morphology is used. HS188 is widely preferred as supper-alloy due to its high oxidation resistance up to 1095°C and creep strength. This property enables the structure to be utilized as part of gas turbine engines operating at elevated temperatures. Main disadvantage of high temperature super alloys is related to their weight. Therefore, utilizing the high strength to weight ratio of structural lattices with a high temperature super alloy shows considerable amount of potential especially for lightweight and performance requiring high temperature applications. Essential material properties of HS188 are illustrated in Table 2. However, in AM perspective, specialized HS188 powder for powder bed additive manufacturing systems are not wide-spread and parameter sets for processing this material is found not to be commercially available. Acceptable powder size distribution of the Concept Laser M2 is recommended to be in the interval of 10-70 µm.

Table 2: Material properties of HS188 [16]

Density (g/cm3)	Poison's Ratio (-)	Young's Modulus (GPa)
8.98	0.3	232

Three DG specimens including 6, 8, and 12 mm unit cell sizes are manufactured as 24x24x24 mm cubes at same volume ratio. Fabricated test samples are illustrated in Figure 2. After completion of manufacturing process, specimens are welded to a steel plate and the entire process chamber is completely filled with powder. This powder is required to be evacuated from the chamber and the parts must be cleaned of powder residues. Once cleaning phase is done, samples are ready for compression test in order to identify elastic material properties.

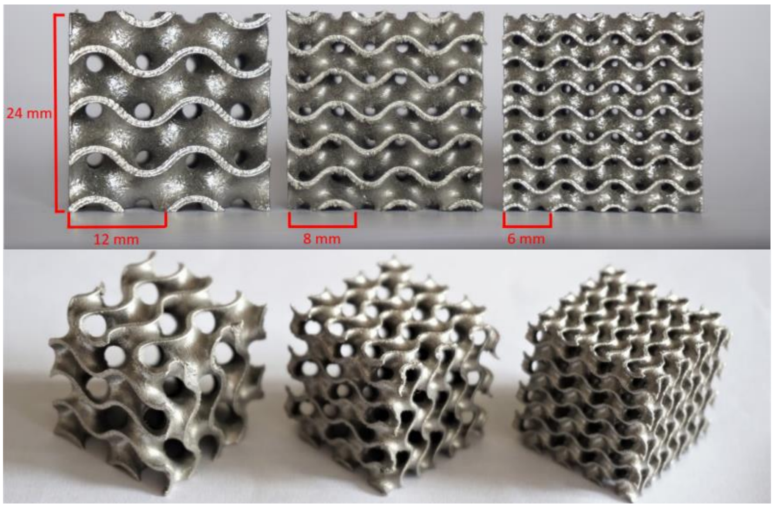


Figure 2: HS188 DG samples from left to right with 12, 8 and 6 mm unitcell sizes respectively

2.3 Compression Tests and Results

Lattice structures have recently been extensively studied to understand their mechanical properties under certain loading conditions. Aforementioned design parameters of lattices such as unit cell types and geometrical aspects are found to have significant effect on the failure mechanisms of lattices. Fundamental mechanical properties for critical design solutions such as yield stress, ultimate stress and energy absorption prior to densification and elasticity modulus of lattice structures are required to be documented for design assessments. To characterize the mechanical properties of double gyroid structure to research its potential in aforementioned application areas, the compression characteristics is of great consideration. The rate of compression in the compression testing is set to 1 mm per minute since it is the lowest strain rate available. Each specimen is placed on the compression fixture in the build direction in order to avoid the effect of anisotropy.

Representative force-displacement and stress-strain curves from compressive testing of three different DG lattices at same volume ratio presented in Figure 3. Each stress-strain curve exhibits four distinct regions: linear region, beginning of non-linear regime which reaches to maximum stress point, then plateau phase and finally pure densification regime. However, it is aimed to investigate linear response of DG structure as part of the proposed methodology enabling computational efficient modeling of large scale cellular structures. Stress-strain and force-displacement graphs cover linear region and early non-linear region results.

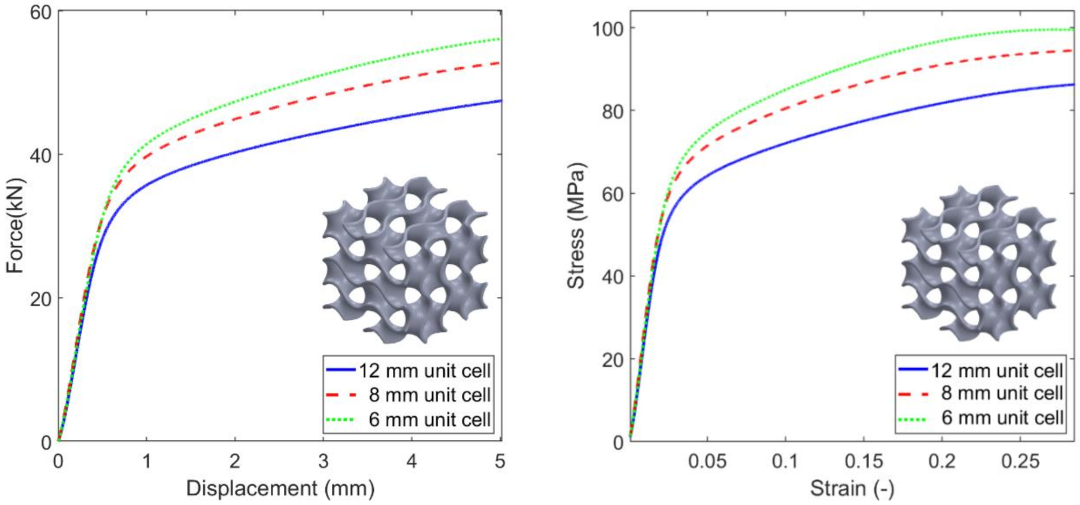


Figure 3: Compression test results for each unit cell

The elastic modulus extracted from the linear elastic regions, where the slope of linear curve represents the elastic modulus, for all three different gyroid specimens with different unit sizes are given in Table 3. These results show that average elastic moduli of individual unit cells are quite similar. These mechanical properties are utilized to validate numeric methods and to simplify complex gyroid structure to bulk geometry.

Table 3: Yield stress and elastic modulus for each unit cell size specimen

Unit cell size (mm)	Yield stress (MPa)	Elastic modulus (GPa)
6	67.3	2.7
8	60.1	2.8
12	51.4	2.5

3 FINITE ELEMENT METHOD AND MODAL TESTING

It is common in literature to model the gyroid lattice structures explicitly as hexagonal solid finite elements or ten-node tetrahedral elements. In addition, it is observed that the previous studies are limited to relatively small unit cells in order to avoid high CPU times [17, 18]. Our objective, in this study, is to investigate the dynamic performance of a 192x192x25.6 mm sandwiched gyroid structures using finite element method. Therefore, it is not appropriate to model gyroid unit cells explicitly using hexagonal or tetrahedral elements due to geometric complexity of the structure and the computational efficiency. Therefore, an alternative approach is proposed in this paper, which makes use of the experimental data. The details of the proposed methodology are explained in this section.

3.1 Modal Analysis of Sandwiched Gyroid Structure

Undamped natural frequencies and mode shapes depend on the overall system stiffness and mass. Hence the accurate estimation of elastic modulus and overall mass of the structure is critical for the accuracy of the modal analysis. Elastic moduli of test samples with different unit cell sizes were determined from compression test as explained in Section 2.3. These mechanical properties are used to analyze a novel structure consisting of 64 unit cells sandwiched between two plates. This structure, shown in Figure 4, is additively fabricated. The properties of the specimen are given in Table 4.

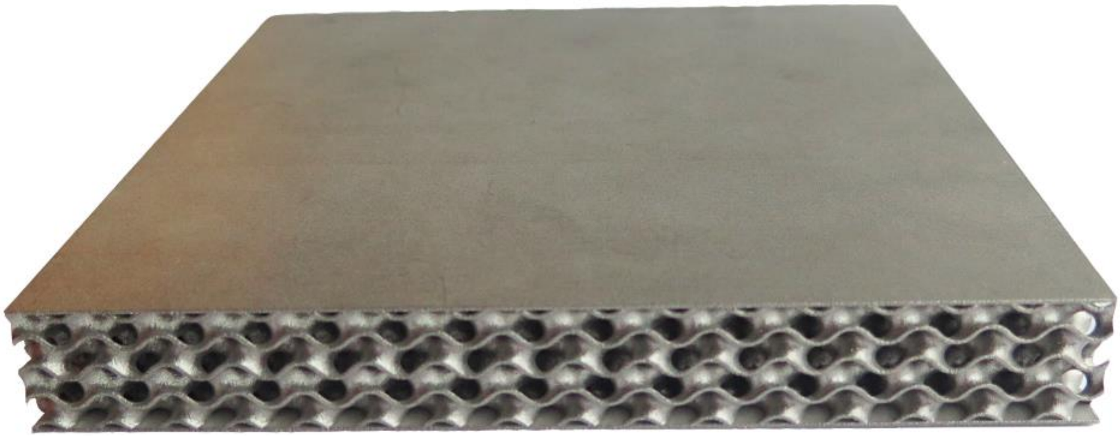


Figure 4: Sandwiched gyroid structure of 192x192x25.6 mm

Table 4: Properties of different test specimens

Unit cell size (mm)	Thickness (mm)	Volume (mm^3)	Cell count	Volume fraction
6	0.4	181120	6144	0.20
8	0.533	181120	1728	0.20
12	0.8	181120	512	0.20

The proposed methodology for modelling complex gyroid structure for an efficient FE analysis is presented in Figure 5. The first step is to determine the elastic modulus of the test specimen from stress-strain curves obtained from compression test. These curves do not refer local stress and strain on the gyroid walls, but capture stress and strain characteristics of entire structure, derived by dividing the applied force by the specimen area of 576 mm^2. The elastic modulus of gyroid test specimens, given in Table 3, is simply calculated from Eq. 2 as:

$$E_{gyroid} = \frac{F \, x \, L}{A_c \, x \, d} \tag{2}$$

where, E_{gyroid} is the elastic modulus of test samples extracted from stress-strain curve, A_c is cross-sectional area of gyroid domain (576 mm^2 for our case), F is the from the magnitude of the force applied during compression test, L is the height of gyroid and d is the displacement of the top surface in the loading direction.

Once elastic modulus is determined, a preliminary FE analysis is performed on a 24x24x24 mm solid cube as part of the complex gyroid topology. For this purpose elastic modulus value, E_{gyroid}, from Step 1 is assigned to the finite element model of representative cube and an iterative static analysis is performed. During the static analysis, the loadings are applied to the FE model replicating the compression test slope from compression test. Once experimental and representative models exhibit same mechanical characteristic, tuned elastic modulus is set as, E_{cube}, which is considered as the equivalent elastic modulus of cube.

In Eq. 2 projection area of gyroid structure is used in accordance with common practice of cellular structure. However, the effective cross-sectional area of gyroid structure is not equal to full projection area and it depends on design parameters of gyroid such as unit cell size and wall thickness. Additionally, cross-sectional area of gyroid slightly varies along the height of gyroid structure and therefore determination of this quantity is more difficult. On the other hand, it is known that volume ratio (VR) directly depends on the cross-sectional area of gyroid structure. Therefore, in this study, we assumed that effective elastic modulus of gyroid form, E_{eff}, can be expressed as in Eq. 3:

$$E_{eff} = E_{cube}/VR \tag{3}$$

The elastic modulus from Eq. 3 can be used as the material properties of the complex geometry. In this study, we fabricated only one sandwiched gyroid structure with 12 mm unit cell size additively for experimental validation.

Gyroid sandwich structure is modelled using 8-noded hexagonal elements. The experimentally calculated elastic modulus is assigned to gyroid portion of the structure. The two plates have thickness of 0.8 mm. Conventional HS188 material properties from Table 2 are used as part of the material model of the plates. FE model of novel sandwich structure is shown in Figure 6. We performed a modal analysis in free-free condition up to 5000 Hz and compared the modes and mode shapes from modal testing. For this purpose, we used Dewesoft hardware/software in modal testing.

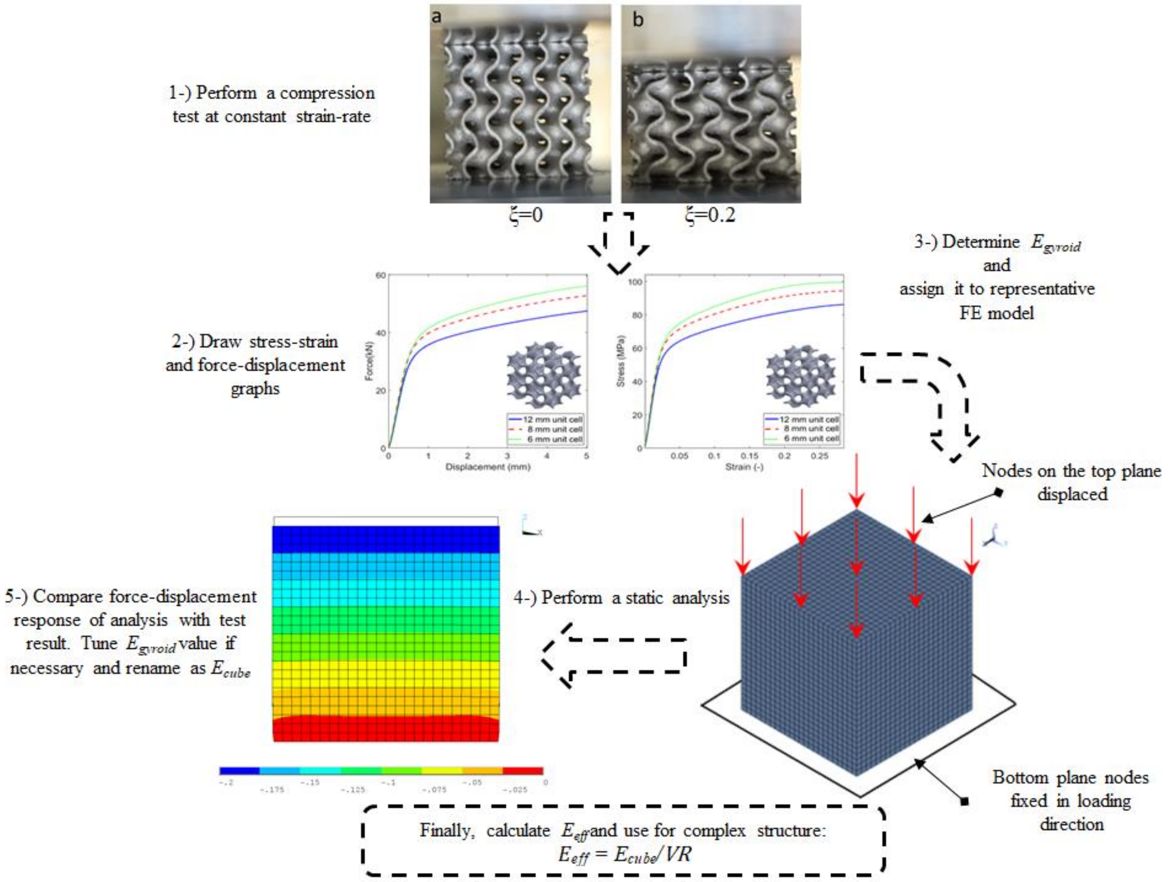


Figure 5: Methodology schematic

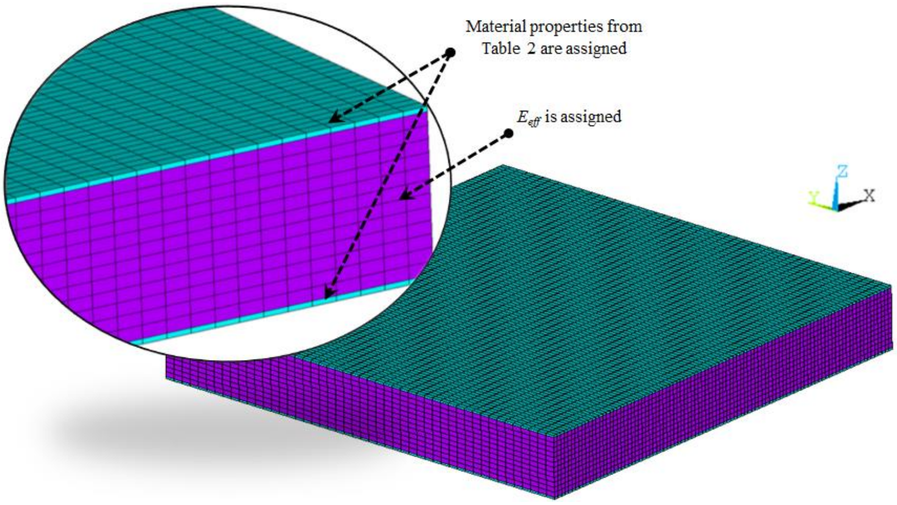
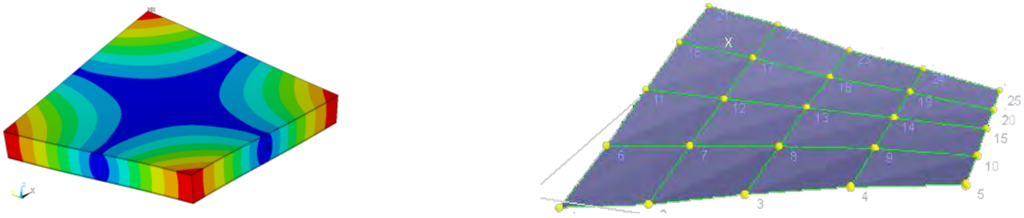


Figure 6: FE model of sandwiched gyroid structure

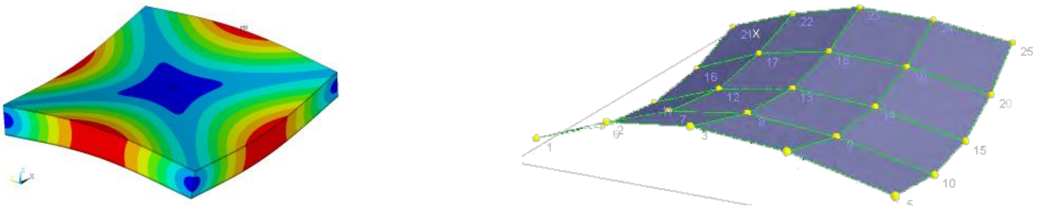
3.1 FE Analysis and Modal Testing Results

Comparison of natural frequencies and mode shapes of gyroid structure for the aforementioned 12 mm unit cells from modal analysis and modal testing are presented in Figure 7. The results indicate a high level correlation between modal analysis and testing. More specifically the relative error on the first 4 modes between modal analysis and testing are 3%, 6%, 4% and 1%, respectively. Also, the computational study is repeated for 6 and 8 mm unit cell sizes using Elastic Modulus from Table 3. The simulations yield the same natural frequencies as in Figure 7. The results from this study show that the modes are directly dependent on elastic modulus. It can also be concluded that the natural frequencies do not change with respect to the size of the unit cell.

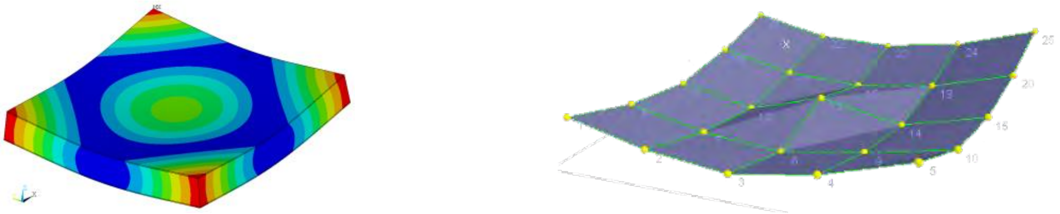
Finite Element Analysis Results Test Results



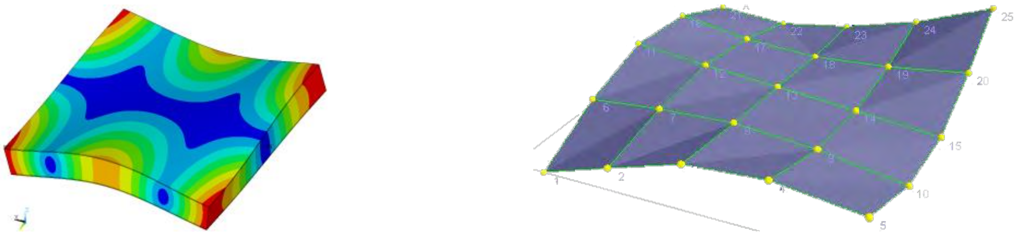
Mode 1: 1832 Hz Mode 1: 1888 Hz



Mode 2: 2787 Hz Mode 2: 2638 Hz



Mode 3: 3348 Hz Mode 3: 3219 Hz



Mode 4: 4287 Hz Mode 4: 4310 Hz

Figure 7: Comparison of modal analysis and modal testing results

Table 5: Properties of different test specimens

Unit Cell Size (mm)	Method	Mode 1 (Hz)	Mode 2 (Hz)	Mode 3 (Hz)	Mode 4 (Hz)
6	Simulation	1855	2820	3393	4358
8	Simulation	1866	2835	3415	4389
12	Simulation	1832	2787	3348	4287
	Experiment	1888	2638	3219	4310
	Relative Error	56 (%3)	149 (%6)	129 (%4)	23 (%1)

4 CONCLUSIONS

An efficient finite element modeling approach is presented in this paper as an alternative to the conventional solid mesh models of gyroid lattice structures. The proposed methodology makes use of the Young's Modulus of the unit cell test specimen, which is determined from compression test. A subsequent static analysis with the Young Modulus from the compression test is performed to derive the equivalent Young Modulus of the full gyroid structure. The proposed methodology is demonstrated on a gyroid structure with dimension of 192x192x2 5.6mm. The results from modal analysis and modal testing show that the proposed methodology can predict the first 4 modes of the structure with a maximum relative error of 6%. The results indicate that the proposed methodology has a potential to develop computational efficient yet accurate models of predicting the dynamic characteristics of gyroid structures. Authors acknowledge the assessment of the correlation of the proposed methodology for forced response of gyroid structures as a future work.

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