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Finite Element Analysis and Validation of Cellular Structures

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Abstract

Additive manufacturing has opened doors to many new technological developments that could not be realised with traditional manufacturing methods. One of these research areas includes the development and utilisation of Cellular Structures in everyday objects. The application of cellular structures theoretically should decrease the required amount of material for production at the cost of overall rigidity and resistance to stresses. This article presents a validation of Finite Element Analysis (FEA) simulations of Cellular Structures with empirical data obtained from compression tests. Parametrised cells with two different materials are evaluated through FEA simulations against selective laser sintered specimens. The cellular structure are modelled with implicit modelling method.

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1. Introduction

1.1. Overview of Cellular Structures

As additive manufacturing is a growing technology, various efforts have been made to research and develop ways to increase the efficiency of production. Some research has been put into performance improvements in the sintering process by optimising laser wavelengths for faster building speed and creating more accurate lasers [1], as well as minimising the amount of material utilised while manufacturing. There is a growing field within manufacturing that aims to reduce the amount of material used in the manufacturing process, theoretically maintaining or even increasing the amount of strength of the object with a reduction in weight [2]; aptly named Cellular Design, which is of direct interest to this project and will thus be the main research area.

Cellular Design is a process where an object is designed to be created through the additive manufacturing process by building layers of cellular structures upon themselves until the final product is produced. A cellular structure is an object that can be manufactured from materials of varying densities [3], possessing internal micro structures that reinforce and strengthen the object. Essentially, they are the utilisation of periodically repeating unit cells that interconnect in three dimensions. Cellular structures can thus be ultimately defined as objects that possess internal symmetrical geometric micro-structures that are much smaller than the overall size.

These 3D structures are intended to utilise existing structures in nature [4], imitating geometric structures such as honeycombs, cork, porous bone structure and trusses in order to utilise their benefits. The lattice structures utilise tessellating cells to fill a desired volume; they can be created from any form of repeating pattern as long as they interconnect in three dimensions.

Each unit cell is essentially described by three parameters dictating its volume; (a) length, (b) width and (c) height. Because it is extremely important to create a repeatable cell, the parameters are usually made equal to each other to create a unit cube to ensure that a significant amount of shapes can be filled with tessellations and variations of the cell. However, since each parameter could potentially be modified individually, the definition of a cellular structure becomes extremely broad in the sense that any structure that can be identified to be comprised of a tessellated single cell can be counted as a cellular structure. Thus, in this study, the definition of a cellular structure is restricted to a basic unit cube on a meso-scale size (between 0.1 to 10 mm).

1.2. Design and Manufacturing

A significant benefit of the utilisation of cellular structures is that it is superior to traditional methods of subtractive manufacturing due to the reduced requirement of material, time, and energy. Because cellular designs feature large voids within and in-between cells, there can be a significant reduction of utilised material because there is no material loss due to subtractive manufacturing methods such as milling or lathing [5]. They consume less time to produce as opposed to solid designs as

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there is less material required to sinter in the DSLS and DSLM methods [2]. Significant amount of energy consumption reduces directly dependant on the surface area being laser sintered when compared to sintering a solid block of identical volume [6].

The cellular structure design is especially important in application due to its inherent high performance nature - producing very high strength designs with relatively low mass. They also are extremely good at energy and shock absorption, as well as well as being good thermal and acoustic insulators [7]. Although the technology to manufacture structures at the mesoscale and the microscale is increasingly becoming more advanced, there is an extremely large separation between traditional design and more advanced design that takes advantage of the additive manufacturing technologies such as SLS and SLM. There is a distinct lack of a rule of thumb during the design of cellular structures, which in turn causes a portfolio of existing cellular structures to be lacking, hampering the amount of structures that can be implemented.

1.3. Cellular Structure Generation

Existing methods of cellular structure generation typically utilise a manual editing of geometry to achieve the final product. The procedure of creating a structure is usually automated [8], wherein the ends of the unit cell have their faces removed and then are joined via a boolean technique with other cells to create a larger structure. This technique is also utilised in creating different cellular structure types [9], utilising cylinders and polyhedral geometric shapes to form innovative designs. These recreation methods are various and well defined, however many manual short cuts are taken in order to achieve a final product, including repairs to geometrical errors by applying spherical junction at each node to smooth the connection and strengthen the structure as it was built [9]. There exists also an innovative concept of Prefabrication Hybrid Geometry Modeling (P-HGM) [10,11] that rapidly generates the cellular structure with boundary representation (B-Rep) and polygonal surface format, STL.

The utilisation of implicit functions was introduced and results in a much better performing structure in compression testing [2]. The utilisation of implicit functions such as triply periodic minimal surfaces become popular due to their ease of manufacturability and the ability to change structure generation parameters in order to achieve optimal structure design for the intended purpose [12].

1.4. FEA on Cellular Structures

Although there is a large amount of research conducted on the generation of cellular structures, there is surprisingly little regarding the simulation of such structures using Finite Element Analysis (FEA). The aim of this study is to explore the behaviour of FEA simulations conducted on cellular structure specimens via inverse testing, utilising data recorded from empirical compression tests. Due to the extremely large cost associated with rapid prototyping of projects for design verification and testing, there is a need to utilise Finite Element Simulation in order to predict the behaviour of the device featuring cellular structure design in order to reduce lead time in manufacturing as well as decrease the overall cost of manufacturing a prototype utilising advanced manufacturing machinery.

A significant amount of variance between empirical results and simulation data has been found repeatedly between a variety of studies which provide evidence of a cumulative error caused in different stages of the experiment procedure. [13] show that there is a significant error between the experimental and theoretical elastic modulus of Nylon-12, whereas [14] demonstrate that there is a significant error between a numerical analysis simulation and traditional FEA modelling in SLS due to the inability to describe the porosity of the sintered material in traditional FEA products.

However, the behaviour of selective laser sintered products has not been examined in detail when they are applied to the manufacturing of cellular structures. This study aims to verify and further investigate the sources of errors in the FEA simulation of cellular structures by using a range of cellular structure types and examine the reasons of failure.

1.5. Organization of this Paper

This paper outlines as follow. The generation of cellular structures, FEA, and manufacturing point of view are in Section 2. Experiments design and result are in Section 3. Discussion and conclusion of this work are presented in Section 4-5.

2. Methodology

2.1. Generation and Manufacturing

In this study, a comparison between simulated and empirical compression tests are undertaken in order to compare the difference between of SLS cellular structure blocks in reality and FEA. To conduct FEA on the cellular structures, they must first be modelled using approximations that accurately represent the family of structures. Once a representation is created, finite element modelling can be undertaken by applying approximations to the empirical testing scheme in order to generate data that can be compared.

The cellular structures, once generated, will be manufactured by using SLS and SLM. The SLS method sinters each atomised particle of the powder together at each edge, unlike the SLM method which melts the powder into surrounding powder to form a mostly uniform object layer.

2.2. Modelling method generation of cellular structure

To generate each cellular structure, a building block, or unit cell, has to be created as a seed for the final cube. Each triply periodic minimalistic surface type that was to be utilised was created with a trigonometric approximation. All solid files were generated in MATLAB 8.5 [15], utilising a variety of parameters to create each cellular structure seed block through their given equations. Two parameters - (a) the thickness of the cell walls and (b) the seed unit cell length - can be varied in order to characterise the cellular structure.

The three different cellular structure types - namely Schoen Gyroid, Diamond, and Neovius (see Fig. 1) - are designed and produced to compare theoretical simulation and mechanical testing results. The equations used for formulating the Schoen