Design, Fabrication and Testing of Fiber-Reinforced Cellular Structures with Tensegrity Behavior using 3D Printed Sand Molds

Nikhil Jorapur

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science
In
Mechanical Engineering

Christopher B. Williams
Alan P. Druschitz
Robert L. West
Carlos T. A. Suchicital

12/13/2016
Blacksburg, Virginia

Keywords: Additive Manufacturing, Cellular Structure, Tensegrity Behavior, Fiber-Reinforcement, Binder Jetting, Sand Casting

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ABSTRACT

The overall goal of this work is to improve the structural performance of cellular structures in bending applications by incorporating tensegrity behavior using long continuous fibers. The designs are inspired by the hierarchical cellular structure composition present in pomelo fruit and the structural behavior of tensegrity structures. A design method for analyzing and predicting the behavior of the structures is presented. A novel manufacturing method is developed to produce the cellular structures with tensegrity behavior through the combination additive manufacturing and metal casting techniques.

Tensegrity structures provide high stiffness to mass ratio with all the comprising elements experiencing either tension or compression. This research investigates the possibility of integrating tensegrity behavior with cellular structure mechanics and provides a design procedure in this process. The placement of fibers in an octet cellular structure was determined such that tensegrity behavior was achieved. Furthermore, using finite element analysis the bending performance was evaluated and the influence of fibers was measured using the models. The overall decrease in bending stress was 66.6 %. Extending this analysis, a design strategy was established to help designers in selecting fiber diameter based on the dimensions and material properties such that the deflection of the overall structure can be controlled.

This research looks to Additive Manufacturing (AM) as a means to introduce tensegrity behavior in cellular structures. By combining Binder Jetting and metal casting a controlled reliable process is shown to produce aluminum octet-cellular structures with embedded fibers. 3D-printed sand molds embedded with long continuous fibers were used for metal casting. The fabricated structures were then subjected to 4 point bending tests to evaluate the effects of tensegrity behavior on the cellular mechanics. Through this fabrication and testing process, this work addresses the gap of evaluating the performance of tensegrity behavior. The overall strength increase by 30%. The simulation and experimental results were then compared to show the predictability of this process with errors of 2% for octet structures without fibers and 6% for octet structures with fibers.

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GENERAL AUDIENCE ABSTRACT

Cellular materials are a class of lightweight structures composed by a network of cells comprising inter-connected struts, which help in reducing the material present in the structure. These structures provide high stiffness for low mass, better shock-absorption, thermal and acoustic insulation. Best known examples in nature include honeycomb, bamboo and cedar. There is a constant desire to improve strength of the cellular structures while wanting low mass. This research aims to provide a new approach towards the enhancing structural performance of cellular structures for bending applications through designs featuring long continuous fibers to impose tensegrity behavior.

The designs in this research are inspired by the structural composition of pomelo fruit and tensegrity arrangements, where continuous long fibers are observed to enhance structural performance. Tensegrity structures are another class of lightweight structures composed of compressive bars and pre-stressed strings/fibers such that the structural elements undergo either tension or compression. The absence of bending stress makes these structures more efficient

A design method for analyzing and predicting the behavior of the structures is presented. To address the imposing manufacturing challenges, a novel manufacturing method is developed, producing cellular structures with tensegrity behavior through the combination of Binder Jetting and metal casting techniques. Binder Jetting is an additive manufacturing process, which selectively binds sand, layer by layer to create molds of desired designs and metal can be cast into the printed molds to realize parts.

The bending performance was evaluated and the influence of fibers was measured using the models. The overall decrease in bending stress was 66.6 %. The fabricated structures were then subjected to 4 point bending tests. The overall strength increased by 30%. The simulation and experimental results were then compared to show the predictability of this process with errors of 2% for octet structures without fibers and 6% for octet structures with fibers. This research takes another step towards creating efficient lightweight structures and adds to the efforts taken to build multifunctional hierarchical cellular materials, which can provide better performance while saving material.

Potential applications of these structures include earthquake resistant wall panels, aircraft fuselage/interior supports, automotive chassis structure, beams for supporting roof loads, armor panels in battle tanks, ship building and packaging (electromechanical systems).

ACKNOWLEDGEMENTS

I would like to thank everyone who has played a crucial role in the pursuit of my Master's thesis:

Dr. Chris Williams, for taking me under your wing and providing guidance, knowledge, and encouragement during my work at Dreams Lab. I'm grateful for your belief and patience that drove this work to completion. Thank you, for making me a better engineer.

Dr. Alan Druschitz, for your insights on materials and assistance throughout my research. Thank you for the patience while imparting manufacturing knowledge in me.

Dr. Robert West, for offering the time and guidance in my analysis. Your teaching has greatly enabled me to conduct this research and complete it.

Dr. Carlos Suchicital, for providing timely advice and being on my review committee.

Erin Connelly, for your expertise and assistance in fabrication.

DREAMS Lab members, for helping me and providing advice during my research work. Thank you for keeping the lab, full of fun, and excitement. I will surely miss you all.

My friends and roommates, who have been a constant source of support and encouragement.

My parents, for their endless love and faith in me.

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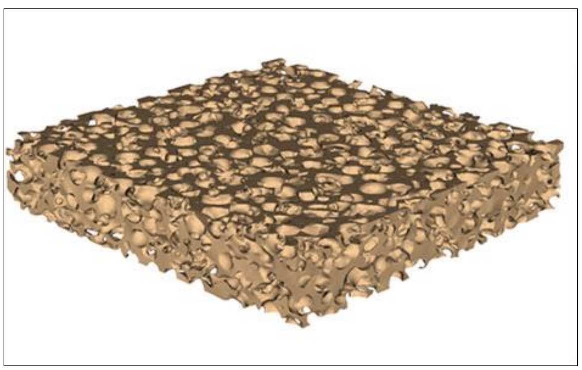
1 INTRODUCTION

1.1 Cellular Materials

Cellular materials are a class of lightweight structures that provide sufficient stiffness and strength with a low mass density for a particular loading [1, 2]. These structures are of great interest due to their efficient structural performance and have been developed for a wide range of applications in automotive, bio-medical, aerospace, sporting, construction and energy-absorption systems [3].

Cellular materials are characterized by a network of cells comprising inter-connected struts, which help in reducing material present in the structure [2]. They are differentiated by the nature of the voids present in the structure, as shown in Figure 1-1. Stochastic materials are composed of cells of random shape, morphology, and distribution [4]. Ordered/periodic cellular materials are composed of an ordered repetition of standard cell topology [5]. Cellular materials featuring designed mesostructures are differentiated by their selective placement of material to achieve multiple design objectives (i.e., the topology is repeatable and controlled but not necessarily periodically repeating) [6].



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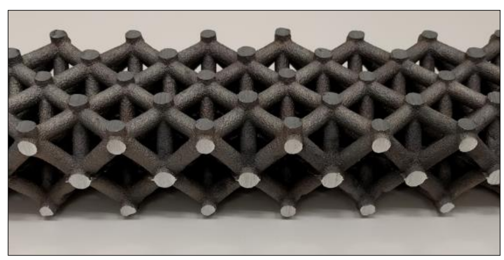


b)

Figure 1-1. Classification: a) Stochastic Foam [7] b) Ordered cellular materials

There is a constant desire to improve strength of the cellular structures while wanting low mass. *This research aims to provide a new approach towards the enhancing structural performance of cellular structures through designs featuring long continuous fibers to impose tensegrity behavior.* This concept is inspired by the structural composition of pomelo fruit and tensegrity arrangements.

1.2 Inspiration: Pomelo and Tensegrity Structures

1.2.1 Pomelo Structure

A study on the skin of pomelo fruit revealed that due to the presence of hierarchical cellular structure with fibrous supports, the fruit could withstand a fall of 10 m without any considerable damage [8]. The peel sample of the fruit was characterized and structural hierarchical levels from intercellular foamy structures to cell-struts were seen. Further inspection revealed long continuous fibrous vascular bundles were distributed randomly within the whole structure. It was concluded that this helped in better energy absorption during the impact. The structural composition of the pomelo fruit is shown in Figure 1-2. This work derives inspiration from the pomelo structure where long continuous fibers enhance the structural performance. Similarly, this study aims to use long continuous fibers to improve the bending performance of octet-cellular structures.

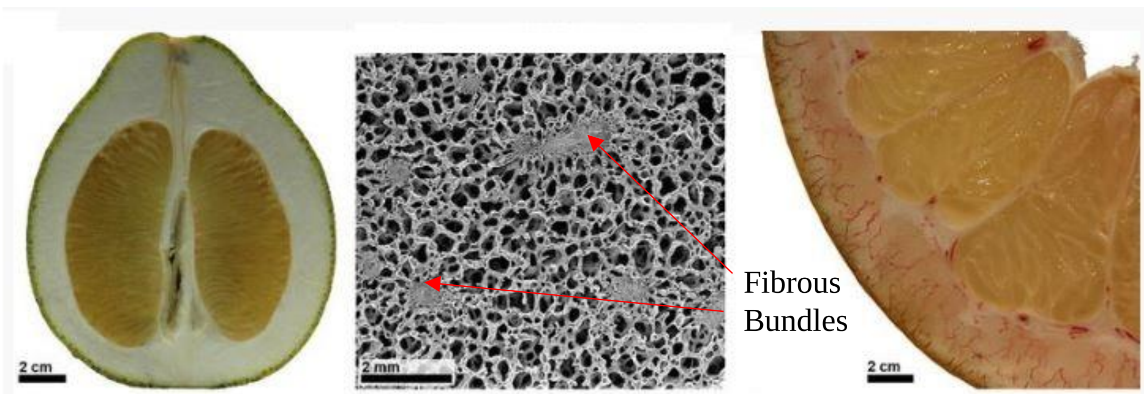
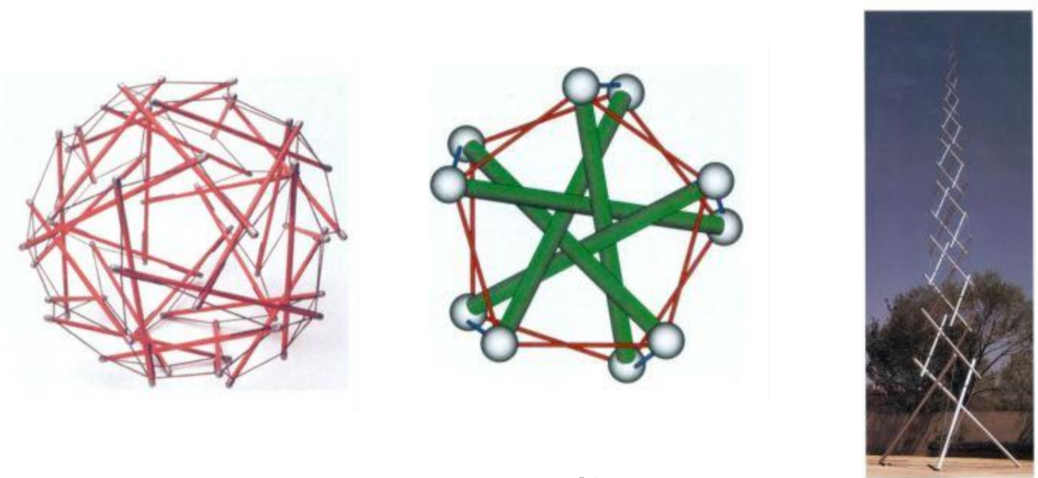


Figure 1-2. Hierarchical structure of pomelo fruit with long continuous fiber reinforcement [9]

1.2.2 Tensegrity Structures

In the context of long continuous fibers, this work is also inspired by tensegrity structures. Tensegrity arrangements as shown in Figure 1-3, are designed to involve only tensile and compression stresses regardless of loading style [10]. The word tensegrity is a reduction of *tensile integrity*, coined by R. B. Fuller through his patent in 1962 [11]. The structure is made of spatial assemblies of rigid compressive bars and deformable pre-stressed strings [12]. In a tensegrity structure, the fibers provide stability to structure and restrict the total deflection of the system. The fibers engage in tension when the system is subjected to loading. Their non-linear mechanical behavior, along with low mass [13] for given loads, make them suitable for lightweight deployable applications. Tensegrity structures can also absorb and distribute energy under different load conditions [14, 15]. The strings help in distribution of compressive stress of rods through their pre-tension and high strength. For example, innovative tensegrity forms of cable domes were used in construction of stadiums during the Korean Olympics [16] due to their lightweight and high strength abilities. A robotic leg was created using the tensegrity arrangement of bone-tendon such that pre-tensioned wires were included to absorb energy and enable high speed running [17].



a) Courtesy: Design Science Toys. Ltd

b) [18]

c) Illustrated by Kenneth Snelson, 1968

Figure 1-3. Tensegrity arrangements a) Courtesy: Design Science Toys. Ltd b) [18] c) Illustrated by Kenneth Snelson, 1968.

The applications of tensegrity structures are limited due to the manufacturing challenges caused by their complexity and are, thus, often fabricated by manual assembly. Due to the complex arrangement of fibers and rods, traditional manufacturing techniques cannot be used for producing tensegrity structures. Although tensegrity designs have been thoroughly studied, the absence of a controlled fabrication process has limited the use of tensegrity structures in real-world applications. In order to address this gap, this work presents the use of a process chain of Additive Manufacturing (AM) and metal-casting (Section 1.4).

1.3 Research Goal

There has been no report in the literature of incorporating tensegrity behavior in cellular structures to enhance structural performance. This gap is mainly present due to the inability of traditional manufacturing techniques to produce tensegrity structures. The only similar approach, which has been explored, is reinforcement of cellular structures using short fibers to gain enhanced strength. Unidirectional carbon fiber/epoxy prepreg laps were hot-pressed to form pyramidal structures with superior compressive strength. [19]. Hollow composite trusses composed of carbon-fibers were arranged to form pyramidal truss structures with high buckling strength using thermal expansion molding [20]. Silicon-carbide filaments were reinforced inside the titanium struts to fabricate millimeter scale lattice structures outperforming other cellular materials with a density of less than 1 g/cm^3 [21, 22]. While these processes were successful in producing fiber-reinforced cellular structures, they are bound by limitations in creating intricate shapes due to the difficulty in creating complex fixtures. Also, these processes are constrained by the usage of expensive fixtures, instruments, and complex procedures. **The goal of this research work presented here is to realize both a design and analysis approach and manufacturing process for fabricating octet-cellular structures with tensegrity behavior through long continuous fibers to improve the performance of structures for bending applications.**

The effort towards fiber-reinforcement of cellular structures can be approached through a tensegrity perspective. In this work, the fiber placement is based on the geometry but not inside the material, unlike the previous studies where short fibers were used. The current techniques used for developing fiber-reinforced cellular structures do not have the capability of selectively placing the fibers. The fibers used were all short and were placed inside the material before realizing the geometries. As shown in Figure 1-2, the fibers in pomelo were within the struts and not across struts.

This work aims to increase the knowledge of incorporating tensegrity behavior in cellular structures and identify the design considerations required to realize such structures (Chapter 2). Also, this research evaluates the consequent effect of tensegrity behavior in cellular structures by studying the bending performance of the designed structures (Chapter 3). The key difference in this design is selective placement of long continuous fibers in cellular geometry. This is extremely challenging for the existing processes, due to the complexity involved in creating fixtures. To solve the manufacturing challenges, this work looks to Additive Manufacturing (AM) techniques, which provide tremendous amount of freedom in designing complex cellular mesostructures (Chapter 3).

1.4 Overview of Proposed Process

The desire for a tensegrity arrangement requires better control over placement of material. The requirement of anchors in metal AM process to reduce residual stresses restrict the freedom to include fibers in desired positions and realize designed mesostructures. To address the limitations of the direct metal AM techniques and current processes used for producing fiber-reinforced cellular structures, this research proposes a process combining Binder Jetting and metal casting technique to develop cellular structures with continuous long fibers.

Binder Jetting process selectively binds sand, layer by layer to create molds of desired designs and metal can be cast into the printed molds to realize parts. Binder Jetting process provides an immense amount of design-freedom in producing complex structures. Binder Jetting along with metal casting can facilitate controlled realization of cellular designs with continuous long fibers, solving the manufacturing challenges of tensegrity arrangements.

A process chain where metal can be cast into complex sand molds printed using Binder Jetting to produce cellular metal structures was established [23]. The proposed process, in this work, expands the use of Binder Jetting to print complex sand molds with provisions to include long continuous fibers and casting of metal into the printed molds to produce designed cellular geometries. The process is described in detail in Section 3.3.

The proposed process is shown in Figure 1-4. Complex cellular sand mold designs are digitally made and split into sections to accommodate long continuous fibers. The sand molds of these digital designs are printed using Binder Jetting. The printed molds are cleaned and next, the fibers are embed in the mold assembly. The metal is then cast and cellular structures with continuous long fibers are realized.

This novel method of embedding fibers and realizing tensegrity structures introduces a new approach of producing complex cellular structures with multifunctional properties. The fibers can embedded in desired orientations to develop complex tensegrity structures that have been modeled but never realized. The structures can be tuned based on design so that they are applicable for multiple conditions.

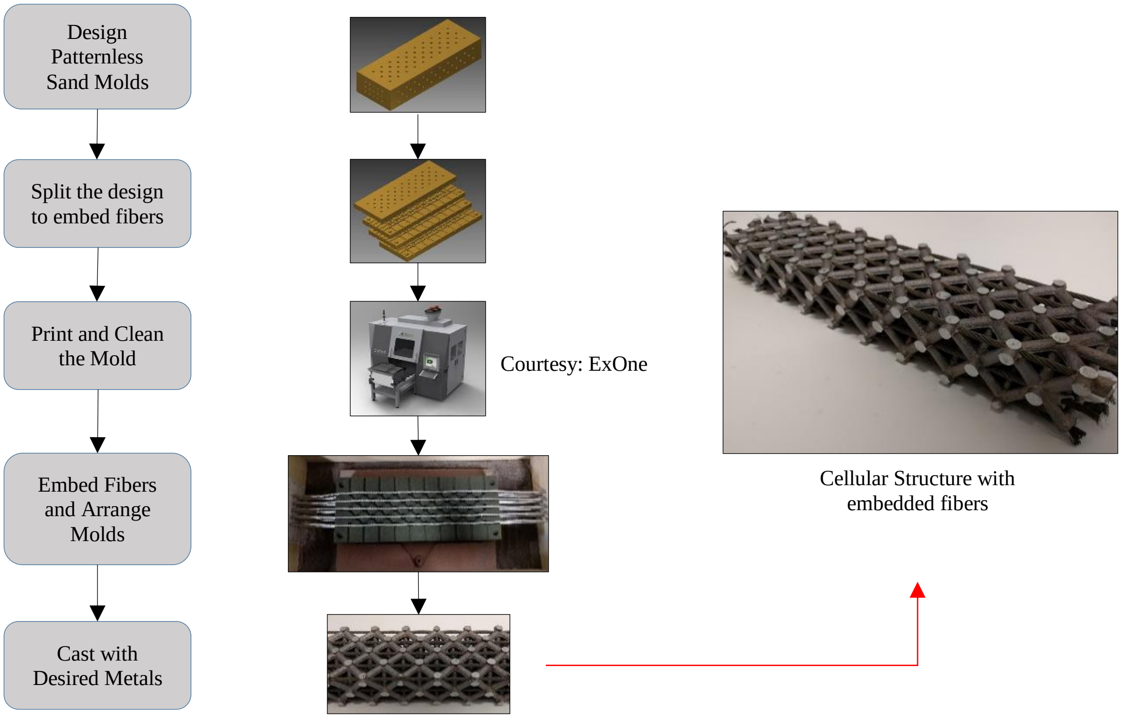


Figure 1-4. Proposed method to create cellular structures with long continuous fibers

1.5 Research Question and Hypothesis

The process of integrating tensegrity behavior in cellular structure mechanics has not yet been explored. The complex arrangement of fibers around the structure has posed a difficult challenge to develop a controlled fabrication technique. Subsequently this has hindered the advances in designing tensegrity systems integrated with other geometries. Since this work aims to design cellular structures with tensegrity behavior as well as develop a process to produce the designed structures and evaluate them, the research questions are divided into two parts; design focused and manufacturing focused.

1.5.1 Design Focused Research Questions

Research Question 1: *What are the design considerations for cellular materials such that tensegrity behavior can be incorporated?*

The concept of tensegrity works due to the appropriate placement of the fibers. To integrate the tensegrity behavior in cellular structures, there is a need to locate the positions of fibers. The mechanics of octet-cellular structures has been studied extensively [1, 23, 24] and the structure is established to be stretch dominated, where only axial stresses are observed when subjected to any type of loading. This understanding can be leveraged to study the mechanics of octet structures with long continuous fibers and produce tensegrity behavior. The decrease in bending stress can be evaluated, for a loading condition, to confirm tensegrity behavior.

Hypothesis: *Fibers can be connected between the nodes of octet cell structure so that they undergo tension while octet structure only experiences axial stresses. This can lead to tensegrity behavior devoid of bending stresses.*

Research Question 2: *How does the tensegrity behavior affect the mechanics of cellular material?*

The technique of designing cellular structures has been established [1, 21, 26]. By understanding the mechanics of octet cellular materials with fibers, and designing the structures such that they mimic tensegrity behavior, the current gap can be addressed. The integration of two different designs, i.e., cellular and tensegrity, needs to be analyzed for understanding the performance of the structures. Analysis of 4-point bending tests on the models can be conducted to measure the effectiveness of fibers. The existing understanding of the tensegrity structures helps in proposing the following hypothesis.

Hypothesis: *The interplay of tensegrity behavior introduced through embedded fibers and mechanics of cellular materials will cause enhanced structural performance under bending applications.*

1.5.2 Manufacturing Focused Research Question

Development Question: *How to fabricate large metal cellular structures with continuous fibers?*

There is a need to develop a controlled reliable manufacturing process to realize cellular structures with tensegrity behavior. For this, a major requirement is the selective placement of fibers.

Development Hypothesis: *Using Binder Jetting AM and metal casting, long continuous fibers can be selectively placed in sand molds to produce cast cellular structures with tensegrity behavior.*

Research Question 1: What is the bending performance of cast metal cellular structures with tensegrity behavior, introduced using long continuous fibers?

Tensegrity structures have been mainly developed by manual assembly of strings and columns. Due to the lack of a controlled manufacturing process, the performance and failure mechanisms of tensegrity structures is not clearly understood [27]. There is a need to develop a process that can produce these structures with a complete control and hence the evaluation can be reliable. Through the combination of Binder Jetting and metal casting, reliable metal cellular structures were produced [23]. To gain a good understanding of the cellular structure behavior, bending tests [13, 24] were used to evaluate their performance. But the cellular structures with tensegrity behavior have neither been fabricated nor evaluated under any loading application. There is a need to understand the performance quantitatively and measure the effects due to the presence of long continuous fibers. Using Binder Jetting AM and metal casting, cellular structures with tensegrity behavior can be produced using long continuous fibers. The cellular structures with fibers can then be evaluated using 4-point bending tests and compared to the structures without fibers. Based on the current understanding of cellular structures in bending tests, the following hypothesis is stated.

Hypothesis: *This controlled process is shown to produce reliable structures. The presence of tensegrity behavior is expected to improve the bending performance of the cellular structures.*

1.6 Roadmap of Thesis

The format of thesis includes planned publications as chapters. Chapter 1, provides the introduction of cellular materials and tensegrity structures, followed by the overall research goal with research questions guiding this work. In Chapter 2, the design process to introduce tensegrity behavior in cellular structures is discussed answering the research questions, shown in Table 1-1. Finite element analysis is used to produce tensegrity behavior through embedded fibers in cellular materials. The analysis is further extended to study the bending performance and provide design criteria based on the effects of fiber on cellular mechanics. Chapter 3 provides the details of the fabrication process and validation of the structures designed based on analysis, addressing the research question in Table 1-2.

Specifically, the fabricated structures are subjected to 4-point bending test followed by material characterization and the results are discussed. In Chapter 4, the key results of this research work are presented along with conclusions and future ideas to improve modeling and manufacturing process.

Table 1-1. Design of Fiber-Reinforced Cellular Structures with Tensegrity Behavior

Design Focused Research Questions	
Research Question 1	**Research Question 2**
What are the design considerations for cellular materials such that tensegrity behavior can be incorporated?	How does the tensegrity behavior affect the mechanics of cellular material?
Hypothesis 1	**Hypothesis 2**
Fibers can be connected between the nodes of octet cell structure so that they undergo tension while octet structure only experiences axial stresses. This can lead to tensegrity behavior devoid of bending stresses.	The interplay of tensegrity behavior introduced through embedded fibers and mechanics of cellular materials will cause enhanced structural performance in the structures.
Methods	**Methods**
By studying mechanics of octet cellular structure and introduce fibers, using finite element analysis	Evaluating the octet-cellular structures with fibers for bending tests using finite element analysis.
Impact	**Impact**
A new design methodology to introduce fibers in cellular structures to gain enhanced performance.	Better understanding of effects of tensegrity behavior/fibers on cellular structures and more control while designing for specific applications.

Table 1-2. Fabrication and Evaluation of Cellular Structures with Tensegrity Behavior

Manufacturing based Research Question	
Research Question 1	**Hypothesis**
What is the bending performance of cast metal cellular structures with tensegrity behavior, introduced using long continuous fibers?	Using Binder Jetting AM and metal casting cellular structures with tensegrity behavior can be produced using long continuous fibers. This controlled process is shown to produce reliable structures. The cellular structures with fibers can then be evaluated using 4 point bending tests and compared to the structures without fibers. The presence of tensegrity behavior is expected to improve the bending performance of the cellular structures.
Methods	**Impact**

Alter the design generation of molds printed using Binder Jetting AM process. Measure the compatibility of fiber and metal being cast through tensile tests. Evaluate the structures based on 4-point bending tests.	A new process to realize cellular structures with tensegrity behavior. Evaluation of cellular structures with tensegrity structures and effects of the embedded fiber. Better understanding of the tensegrity behavior in cellular structures and effectiveness of the long continuous fibers.

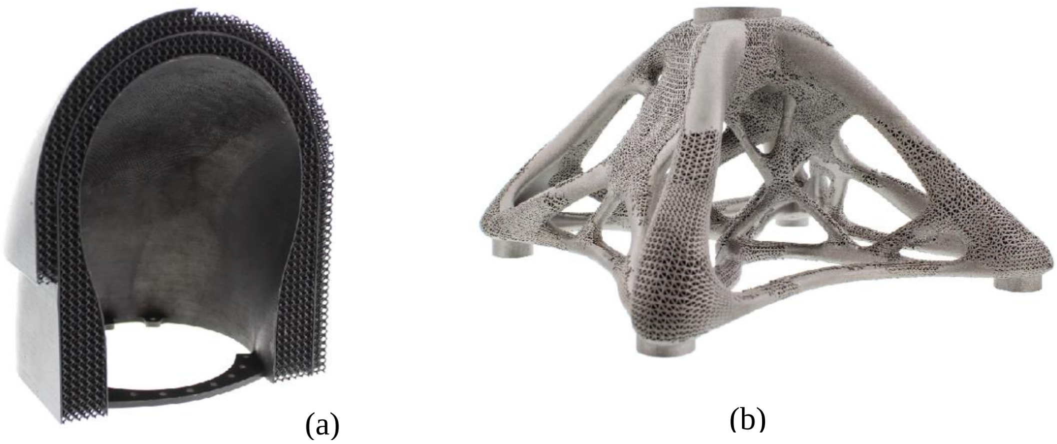
2 DESIGN OF FIBER-REINFORCED CELLULAR STRUCTURES WITH TENSEGRITY BEHAVIOR

Abstract

Tensegrity structures provide a high stiffness to mass ratio since all the comprising elements are either in compression or tension. However, they have limited applications since fabrication of such structures is challenging due to their complexity and are often created through manual assembly of components. This study looks to Additive Manufacturing (AM) as a means to introduce tensegrity behavior in cellular structures to enhance structural performance. This chapter describes design and analysis of octet cellular structures that feature high strength fibers held in continuous tension. Finite element analysis of 4-point bending test is used to evaluate the effectiveness of embedded fibers. Also, the presence of tensegrity behavior was evaluated using this analysis and testing. The structure with tensegrity behavior was found to be 30% stronger. A design strategy was established to help designers in selecting fiber diameter based on the dimensions and material properties such that the deflection of the overall structure can be controlled.

2.1 Introduction

Cellular structures provide high stiffness for low mass, better shock-absorption, thermal and acoustic insulation. Stochastic materials are composed of cells of random shape, morphology, and distribution [4]. Ordered/periodic cellular materials are composed of an ordered repetition of standard cell topology [5]. Studies on periodic cellular structures for loading applications have been motivated by the low structural performance of stochastic cellular structures [28]. Consequently, this has increased interest in the optimization of ordered cellular structures to tailor stiffness and strength for supporting specific loads [29]. Recent research efforts have been directed to design cellular mesostructure, which can perform multifunctional objectives [26, 29, 30]. For example, lattice structures (Figure 2-1a) that provide support, rigidity and heat transfer capabilities were integrated in helicopter gas exhaust nozzle structure [31]. A lattice meso-structure (Figure 2-1b) was combined in an optimized topology to provide sufficient structural strength while minimizing the weight [32].



(a) (b)

Figure 2-1. (a) Gas nozzle [31] (b) Spider Bracket [32]

While cellular materials provide superior structural performance, their applications are constrained by lower elastic moduli and indentation weakness [2, 33]. These structures are predominantly affected by concentrated compressive stresses [34]. Also, the core of cellular topology is reported to suffer local yield or crushing [28, 37, 29]. All these limitations are reported to be affected by strength of the core and cell size [36].

This research aims to improve the performance of octet-cellular structures under bending loads by introducing tensegrity behavior through continuous fiber-reinforcement. Taking inspiration from nature and tensegrity structures, the primary goal is to introduce tensegrity behavior in cellular structures through continuous fiber-reinforcement.

2.1.1 Continuous Fiber-Reinforcement: Pomelo

The design of cellular structures with fibers, in this work, is influenced by the structural composition of pomelo fruit. Nature provides best examples in exhibiting mechanical efficiency where often continuous long fibers are observed to enhance structural performance. Investigation on pomelo fruit, which can withstand a drop of 10 m without significant damage, has revealed that the peel consists of hierarchical cellular structures with fibrous supports that boost energy absorption, as shown in Figure 2-2a [8]. In an effort to create a man-made structure with similar properties, the same research group attempted to produce metal-metal composite structure to mimic pomelo's behavior. Using block mold casting process, tensile test specimens with aluminum (A356) with two different variants of ductility (i.e., outside shell being less ductile) were constructed and evaluated for fracture strength [9], as shown in Figure 2-2b. The testing reported increased strength and strain at the failure when compared to bulk A356, implying more energy absorption. However, the realization of cellular structures with fibers that represent the structural composition of pomelo skin is limited by the reported production process. The process has shown to achieve composite structures inspired by pomelo, but not an exact representation of the hierarchical cellular arrangement present in pomelo.

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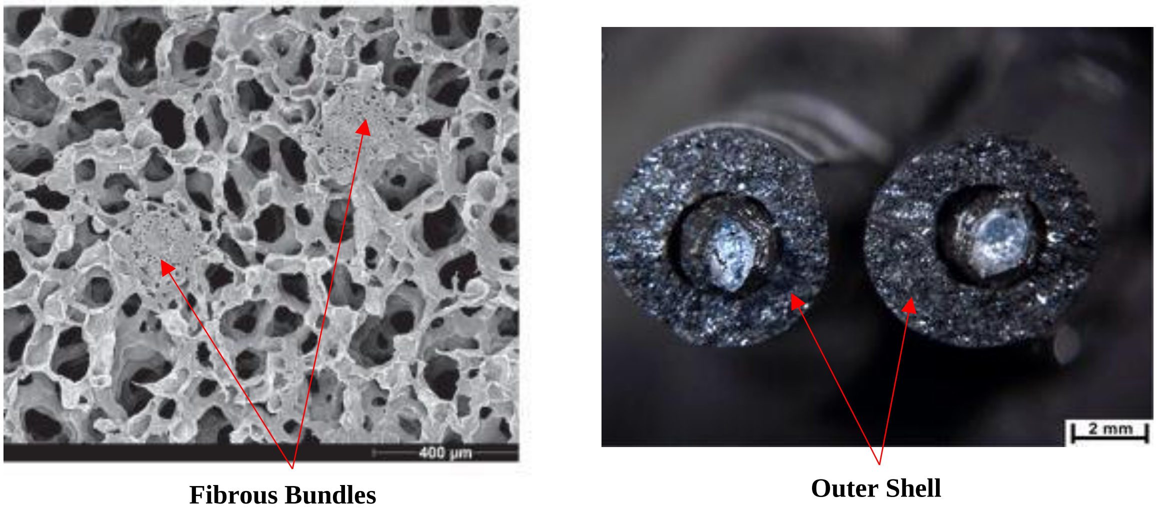


Figure 2-2. (a) SEM image of pomelo peel samples [8], (b) bio-inspired composite [9]

2.1.2 Continuous Fiber-Reinforcement: Tensegrity Structures

In addition to the pomelo structures, the fiber arrangement present in tensegrity structures is also a source of inspiration for the cellular structure design presented in this work (Section 2.2.6). Tensegrity structures, as defined earlier in Section 1.2.2, are composed of compressive bars and pre-stressed strings/fibers such that the structural elements undergo either tension or compression. The continuous arrangement of struts and strings provides high structural efficiency along with lightweight [37, 38].

Tensegrity structural membrane designs have been used in notable constructions such as Redbird Arena and the Suncoast Dome in the United States, the La Plata Stadium in Argentina, and the Tao-Yuan County Arena in Taiwan, China [39]. This is mainly because of the lightweight nature of the structures and the strings provide additional stiffness to avoid large deflections, as shown in Figure 2-3. Also, tensegrity designs have been explored as deployable structures in space applications [15] due to the presence of foldable members.

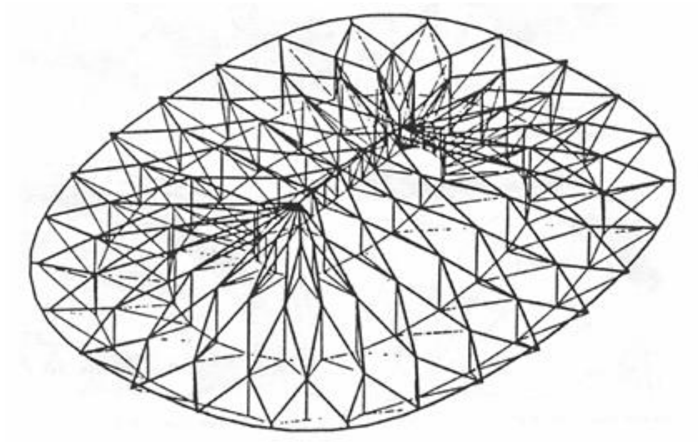


Figure 2-3. Tensegrity Cable Dome Structure [40]

The concept of tensegrity is fifty years old and yet few applications exist. This is because of the complex assemblies that are involved in the structure, which constrain the fabrication using traditional manufacturing techniques. Tensegrity arrangement demands selective placement of fibers, which is extremely challenging for traditional manufacturing techniques.

2.1.3 Manufacturing Process Approach

The research in this work has been inspired by the presence of continuous fibers in the pomelo and tensegrity structures, where performance in terms of energy-absorption and strength has been enhanced. Using continuous fibers, this research seeks to introduce tensegrity behavior and provide a novel means to improve bending performance of cellular structures. To fabricate such structures, there is a need for a process that allows selective placement of fibers. This work looks to AM and metal casting to address the issue of fabrication. AM processes provide tremendous degree of freedom in terms of design, process-control and material placement. Due to the layer-by-layer approach of AM, it is possible to control the build such that fibers can be embedded.

Binder Jetting process selectively binds sand, layer by layer to create molds of desired designs and metal can be cast into the printed molds to realize parts. Binder Jetting process provides an immense amount of design-freedom in producing complex structures. Binder Jetting along with metal casting can facilitate controlled realization of cellular designs with continuous long fibers, solving the manufacturing challenges of tensegrity arrangements.

The proposed process is shown in Figure 2-4. Complex cellular sand mold designs are digitally made and split into sections to accommodate long continuous fibers. The sand molds of these digital designs are printed using Binder Jetting. The printed molds are cleaned and next, the fibers are embed in the mold assembly. The metal is then cast and cellular structures with continuous long fibers are realized.

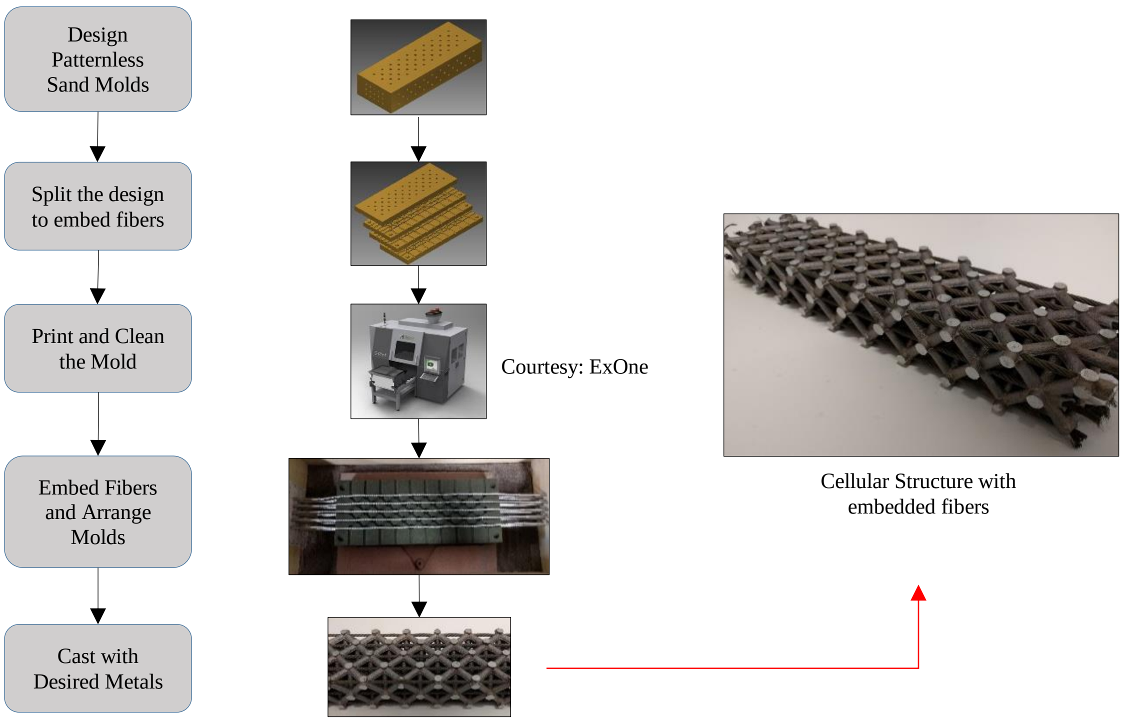


Figure 2-4. Proposed method to create cellular structures with long continuous fibers

For embedding fiber in any AM system, this process can be generalized, where the print needs to be paused to embed fiber and continue printing to attain the final part. During the printing of cellular structures, continuous fibers can be placed based on the user's choice, as shown in Figure 2-5. This process can create high strength light weight structures, which can be directly used in any load bearing applications for any kind of scale.

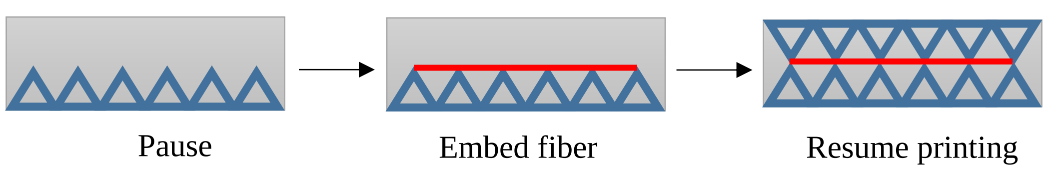


Figure 2-5. Schematic representation of embedding fiber while 3D printing

Potential applications of these structures include earthquake resistant wall panels, aircraft fuselage/interior supports, automotive chassis structure, beams for supporting roof loads, armor panels in battle tanks, ship building and packaging (electromechanical systems).

The current design techniques that exist for producing lattice cellular topologies are described in Section 2.1.4 and the reasons for a new design method are discussed. For this fabrication process of embedding fibers in cellular structures there is a need for design technique to achieve tensegrity behavior. Clear understanding of the interplay between fibers and cellular geometries needs to be established before proceeding with the design process.

2.1.4 Design: Lattice Cellular Structures

In the context of cellular structures, this research is related to the design of lattice structures. Lattice Structures have stretch dominated unit cells and hence differ from open cell foams in terms of rigidity and load bearing capabilities. Development in designing and analyzing new lattice topologies have been based on the method established by Gibson and Ashby [2]. The method involves analysis based on the geometry and a relationship between the relative density and loading is determined, which is further expanded to study the effective properties and collapse mechanisms of the cellular structure [2, 41].

In addition to analytical methods, finite element solutions have also been implemented to validate the performance of the overall structure. For example, effective properties of octet cell structure were derived using both analytical and finite element solutions [1]. Also, in the context of reinforced cellular structures with short fibers were also evaluated using the similar design and analysis methods. For example, titanium square and diamond lattice structures [21] reinforced with short silicon carbide fibers were structurally tested and validated using analytical solutions based on relative density approach [22].

The current design techniques exist specifically for cellular structures, which are based on types of cells used in the topology. The existing design methods are either being used in creating optimized cell topologies or fiber reinforced cellular structures to achieve improved structural performance. The design methods used for fiber-reinforced cellular structures cannot be applied in this work. All the efforts in fiber-reinforcement of cellular structures has been inside the core of the material as shown in Figure 2-6.

In this work, the placement of fibers is different than the aforementioned fiber-reinforcement studies. This research concentrates on using long continuous fibers in a cell topology and not on creating new cell type. In this work, octet cellular structure has been selected for achieving tensegrity behavior. The mechanics of this cell type is already established [1]. Therefore, there is a requirement to present the design considerations and methods necessary for building cellular structures with tensegrity behavior.

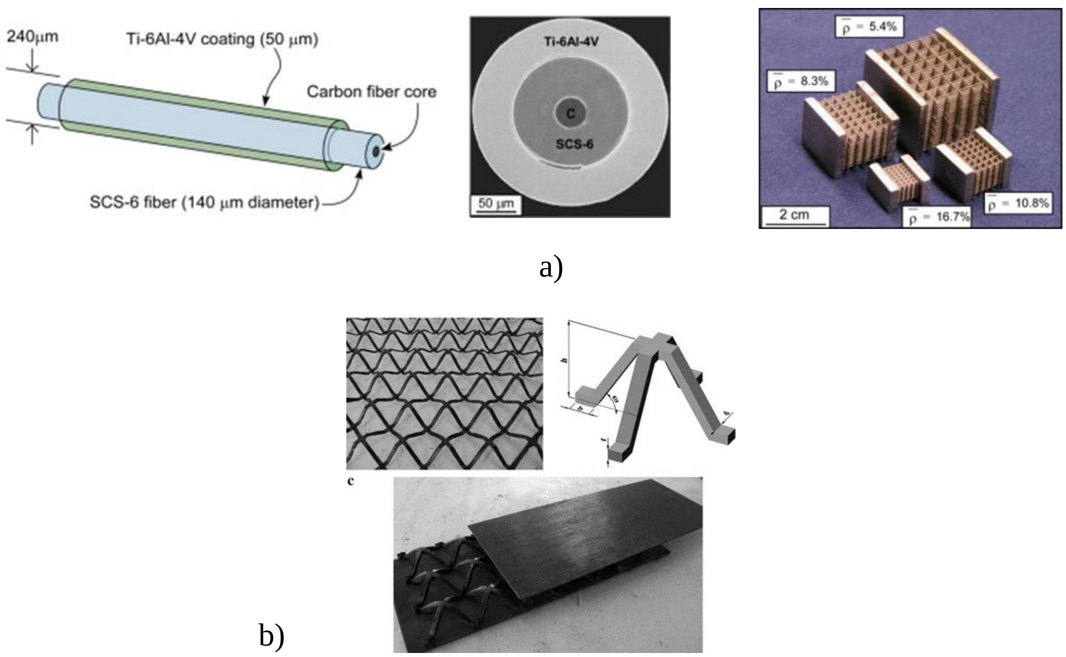


Figure 2-6. Fiber Reinforcement in different topologies [21] (a) Fiber-reinforcement in titanium matrix lattices (b) Pyramidal truss reinforced with carbon-fibers [19]

2.1.5 Goal and Roadmap

This work aims to integrate cellular structure with tensegrity behavior, and provide a methodology to design such structures. The main goal here is to design octet cellular structures with tensegrity behavior through fiber-reinforcement and increase the structural performance for bending applications. **This work is directed to produce a reliable analysis technique and explore conditions under which tensegrity behavior could be integrated with cellular structures.** This chapter of the research addresses the design-focused research questions, which are as follows:

Research Question 1: *What are the design considerations for cellular materials such that tensegrity behavior can be incorporated?*

The concept of tensegrity works due to the appropriate placement of the fibers. To integrate the tensegrity behavior in cellular structures, there is a need to locate the positions of fibers. The mechanics of octet-cellular structures has been studied extensively [1, 24, 25] and the structure is established to be stretch dominated, where only axial stresses are observed when subjected to any type of loading. This understanding can be leveraged to study the mechanics of octet structures with long continuous fibers and produce tensegrity behavior. The decrease in bending stress can be evaluated, for a loading condition, to confirm tensegrity behavior.

Hypothesis: *Fibers can be connected between the nodes of octet cell structure so that they undergo tension while octet structure only experiences axial stresses. This can lead to tensegrity behavior devoid of bending stresses.*

Research Question 2: *How does the tensegrity behavior affect the mechanics of cellular material?*

The technique of designing cellular structures has been established [1, 21, 26]. By understanding the mechanics of octet cellular materials with fibers, and designing the structures such that they mimic tensegrity behavior, the current gap can be addressed. The integration of two different designs, i.e., cellular and tensegrity, needs to be analyzed for understanding the performance of the structures. Analysis of 4-point bending tests on the models can be conducted to measure the effectiveness of fibers. The existing understanding of the tensegrity structures helps in proposing the following hypothesis.

Hypothesis: *The interplay of tensegrity behavior introduced through embedded fibers and mechanics of cellular materials will cause enhanced structural performance under bending applications.*

Finally, this work proposes a method for enhancing structural performance of cellular structures. Section 2.2 explains the modeling approach undertaken in this paper to design cellular tensegrity structures and results to prove structural efficiency. Section 2.2.8 discusses the tensegrity behavior observed in the designed structures and the design criteria, which can be followed to design structures described in this paper. Finally, Section 2.4 provides the closure for this work with future recommendations.

2.2 Modeling and Analysis

2.2.1 Overview

To address the need of integrating tensegrity behavior with cellular structures, the following design and analysis steps was undertaken to establish a design of octet cell structure with long continuous fibers.

The first step was to identify the appropriate positions in cellular structure to locate fibers. For this, a 2D study on a truss arrangement was studied using finite element analysis. The truss arrangement, as shown in Section 2.2.2, is used as an example to represent 3D cellular structures in 2D. The structure was studied under 4-point bending test conditions and the fibers were placed at the nodes, where the displacements orthogonally occurred to loading direction. The truss arrangement with fibers experienced lower stresses and deflection.

Next step was to extend the 2D study to a cellular geometry. For this, 3D beam finite element analysis was conducted on octet cellular structure. The fibers were located at the nodes of the cell, similar to the 2D study, such that they engaged in tension (Section 2.2.4). These structures were subjected to 4 point bending test and the effectiveness of fibers were measured based on deflection and stresses. The study showed that the stresses decreased by 66 % and deflections decreased by 45%.

Finally, to confirm the tensegrity behavior, 3D solid finite element analysis was conducted for the same design from 3D beam analysis. Solid geometry of the cell was built with fibers connected at nodes, as shown in Section 2.2.6. The bending stresses occurring in the struts due to 4-point bending was studied. The octet structure with fibers experienced lower bending stresses (about 83% less) when compared to the structures without fibers.

Through a combination of these three steps, it was possible to; i) identify suitable positions for fibers, ii) measure effectiveness of fibers with improved strength and stiffness under 4 point bending test and iii) confirm tensegrity behavior in octet cell and thus, answering the design focused research questions.

The design variables considered for the analysis conducted in this work are listed in Table 2-1. The design decisions for these variables have been explained in the following sections.

Table 2-1. Design variables

Cell Topology	Fiber Material Properties
Strut Material Properties	Fiber Diameter
Strut Diameter	Overall Size
Strut Length	Fiber Location

The finite element analysis was conducted using ABAQUS/Explicit [42]. For the analysis, the material is assumed to be isotropic, homogeneous and hookean for elastic deformations. The bonding between the cellular material and fiber material is assumed to be perfect (no slipping). The structures are subjected to 4-point bending test and the bending performance is evaluated in terms of stresses and displacements occurring in the elastic region.

2.2.2 Truss 2D Finite Element Modeling – Concept Study

A two-dimensional arrangement of trusses was created to identify the location of fibers. Figure 2-7a shows the structure, which was studied to establish the concept of including high-strength fibers to achieve tensegrity mechanics in cellular structures. This study was a computationally inexpensive method to represent cellular structures and provide guidance for embedding fibers.

Strut material properties: For the analysis studies, Aluminum 6061-T6 was chosen as the material for trusses and cellular structures. The material was given an elastic modulus of 68.9 GPa [43] and Poisson's ratio of 0.33 [43].

Strut diameter: Strut diameter was chosen to be 7 mm to ensure the complete filling of mold while casting [23] and also allow sufficient space for bonding with fiber. It is essential for bonding to occur so that the wires are engaged completely in tension. The wires would otherwise slip in their place and not contribute towards load distribution.

Strut length: Using the Euler-Johnson curve for aluminum as reference, the truss dimensions were chosen such that the struts did not fail due to buckling. For a short column slenderness ratio of 24.5, the strut length was chosen to be 25 mm.

Fiber material properties: The fiber was assigned the material properties of stainless steel wire type 302 with elastic modulus of 193 GPa [44]. Compatibility tests that were conducted (Appendix A), and the tests revealed that steel wires increased the strength tensile strength of specimens and thus, it was chosen as fiber material.

Fiber diameter: A diameter of 1/8 inch was selected based on the parametric study conducted in Section 2.3. The parametric study considers all the design variables (Table 2-1) and provides a solution for choosing fiber diameter to tune the structure for specific loads and displacements. Also, the chosen diameter of steel fiber is a standard size that is commercially available.

The structure was subjected to 4-point bending test where the loads were applied parametrically and the displacement of the center point was noted for each loading condition. The trusses were all represented by 2D beam elements – B21, the Timoshenko beam elements meant for short columns. The loading and boundary conditions were set for 4-point bending tests. The loading points are indicated in Figure 2-7a. One end of the structure was pinned while the other end was allowed to move only in X-direction (roller).

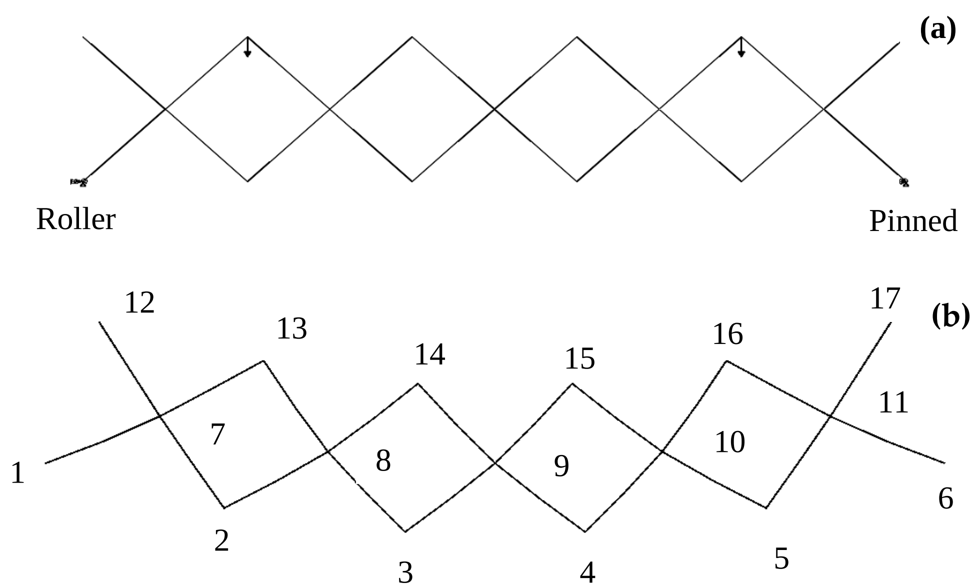


Figure 2-7. 2D Truss (a) loading and boundary conditions, (b) deformed state after loading

2.2.3 Results of 2D model

The displacement of the points in the 2D Truss structure was studied for bending load conditions. Nodes 1, 2, 3, 7, 8 and 9, as shown in Figure 2-7, were investigated since the structure is symmetric and the displacements would be the same for the corresponding mirrored nodes. Also the nodes on the top will have the negative displacement with the same magnitude as the corresponding bottom nodes.

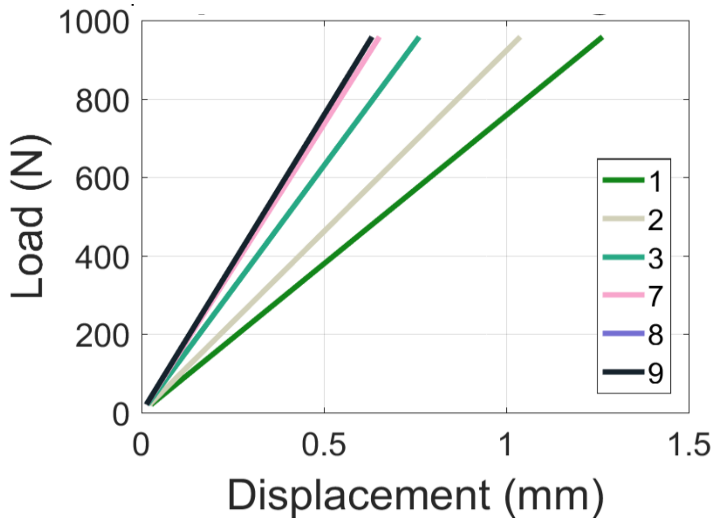


Figure 2-8. Displacements (orthogonal to loading direction) at selected nodes

Points where displacement occurred orthogonally to the loading direction were noted. Nodes 1, 2 and 3 and thus, 4, 5 and 6 show high displacements. These points are candidates for placement of continuous fiber reinforcement. If a fiber were to be placed at these points, the displacements along the orthogonal direction would cause the fiber to be placed in tension, and thereby distributing the stresses from struts. The net displacement is nearly zero at the point (9) lying in center since they lie on the neutral axis of this truss arrangement.

2D-analysis of the same truss-arrangement with fiber inclusions was conducted to test the effect of fiber at these nodes. The material properties of the truss, meshing scheme, loading and boundary conditions all remained the same as the previous study. For the fiber material, stainless steel wire type 302 (elastic modulus = 193 GPa [44]) was chosen with a standard 1/8 inch diameter. The fiber was modeled as a T2D2 (no bending) truss element with no-compression to deactivate, as fibers do not provide stiffness against compression loading.

Figure 2-9a shows the placement of fibers. The fibers were placed on the top layer to maintain the symmetry of structure for loading. The truss arrangement here, is considered to be a section of a multilayered truss structure. Hence, the fibers were located in the center as well, to represent that the fibers would engage in a multilayered truss. It is important to note that the fibers connect the nodes of the cellular structure to fulfill the purpose of incorporating tensegrity behavior. Also, due to the pre-stressing, the fibers in the top layer would engage even if they are under compression. However, this work does not concentrate on the effects of pre-stress, but rather lays out the concept of fiber-arrangement such that tensegrity behavior is seen.

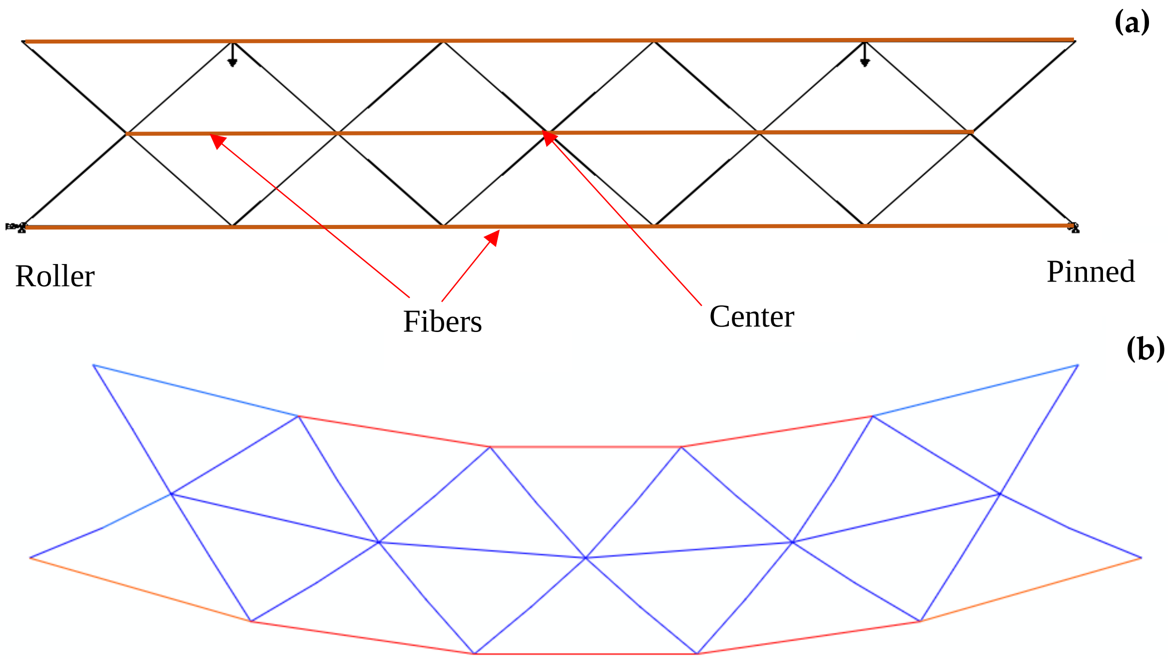


Figure 2-9. (a) Fiber - included in truss, (b) Deformed truss with fibers

Figure 2-9b represents the deformation of structure with fibers. The performance was measured in terms of displacement in direction of loading at the center of the structure and the stresses associated with it. Figure 2-10a and Figure 2-10b depict the displacement (Y-direction) and stress of the center and for parametric loading on the structures respectively. The slope of curve for truss with fiber is greater, implying the structure has become stiffer.

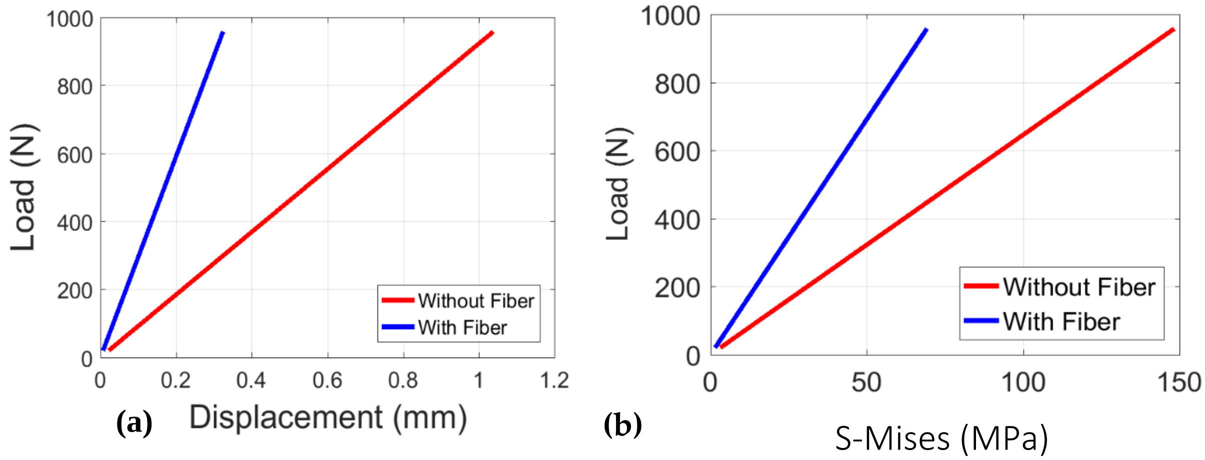
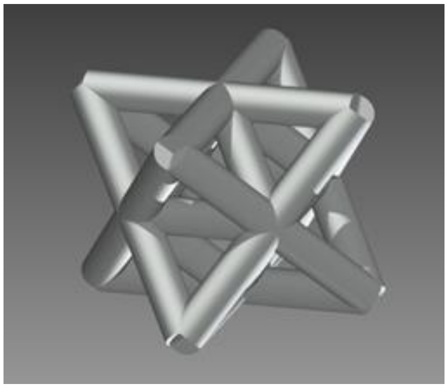


Figure 2-10. (a) Load vs displacement at center, (b) Load vs stress at center

It is noted that the slope of the curve with fiber is much steeper than the truss arrangement with fibers. Maximum stress present in the structure with fibers decreased by 79 MPa when compared to the one without fibers. This improvement in strength can be attributed to the appropriate location of fibers, which have been engaged in tension to reduce stress. Given the displacement in truss arrangement with fibers was decreased by 0.43 mm, it shows increase in stiffness. Then in the 2D results, the effectiveness of fibers included in structures was shown to increase stiffness. Therefore, the same methodology was followed while designing octet cellular structures with fibers.

2.2.4 Octet- Cellular Structure Modeling

Cell topology: Octet unit cell, as shown in Figure 2-11, is considered to be stretch dominated core where predominantly axial stresses are experienced under bending loads [1]. These cores can be complemented by fiber, which can act as pre-stressed strings to introduce tensegrity behavior, making the structures more efficient. Therefore, octet unit cell is used in the topology of the cellular structures for realizing tensegrity behavior.



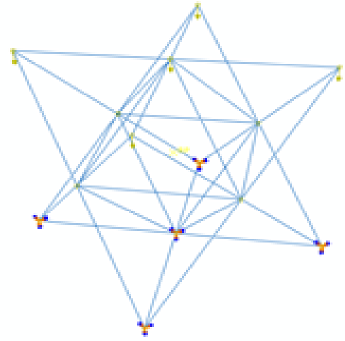


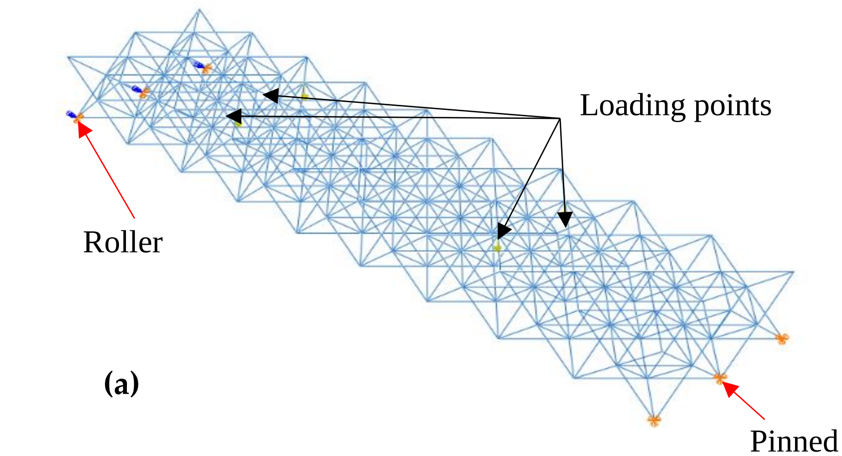
Figure 2-11. Octet 3D Cell Structure

3D Beam analysis was conducted on octet structures to understand the physics of structures and gain insight into the placement of fibers. A 3D Beam structure was built to represent octet geometry as shown in Figure 2-12a. The strut dimensions were based on the same slenderness ratio as selected in Section 2.2.2.

Overall Size: Nine octet cells were repeated in length and two in width to form a structure suitable for 4-point bending test. The overall dimensions were 318.20 mm x 70.71 mm x 35.35 mm, so that the structures were compatible with the testing fixtures.

The structure was assigned Al-6061 T6 material with B-31, Timoshenko beam elements. This was specifically done to confirm the magnitude of bending stress present in the structure. The loading and boundary conditions for 4-point bending test were assigned as shown in Figure 2-12a. As depicted in Figure 2-12b, 3D-beams octet structure was modeled with fibers. As in the 2D model (Section 3.2), the fibers were represented as T3D2 no-compression truss elements since they have no stiffness against compression loads and cannot experience bending loads.

Fiber location: Fibers were included at points as chosen in Section 2.2.2, which was the 2D truss study. The fiber material remained the same as mentioned (steel wire) in Section 2.2.2. Similar loading and boundary conditions were provided as that shown in Figure 2-12b.



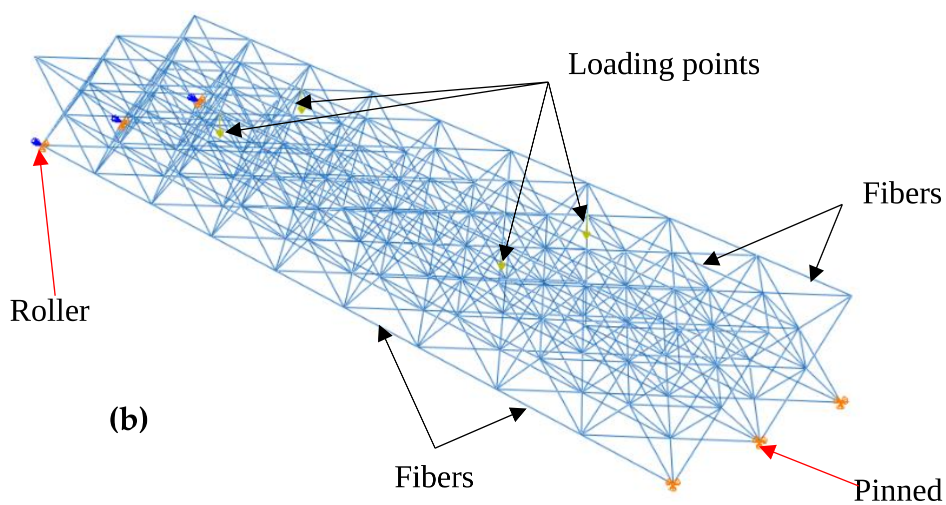


Figure 2-12. (a) Octet cellular with loading and boundary conditions, (b) Octet structure with fibers-loading and boundary conditions

2.2.5 Results

The deformation of the octet structure was studied as shown in Figure 2-13a. Figure 2-13b shows the deformations occurring in octet structure with steel wires. The deformations in both the octet structures were studied in terms of stresses and displacements.

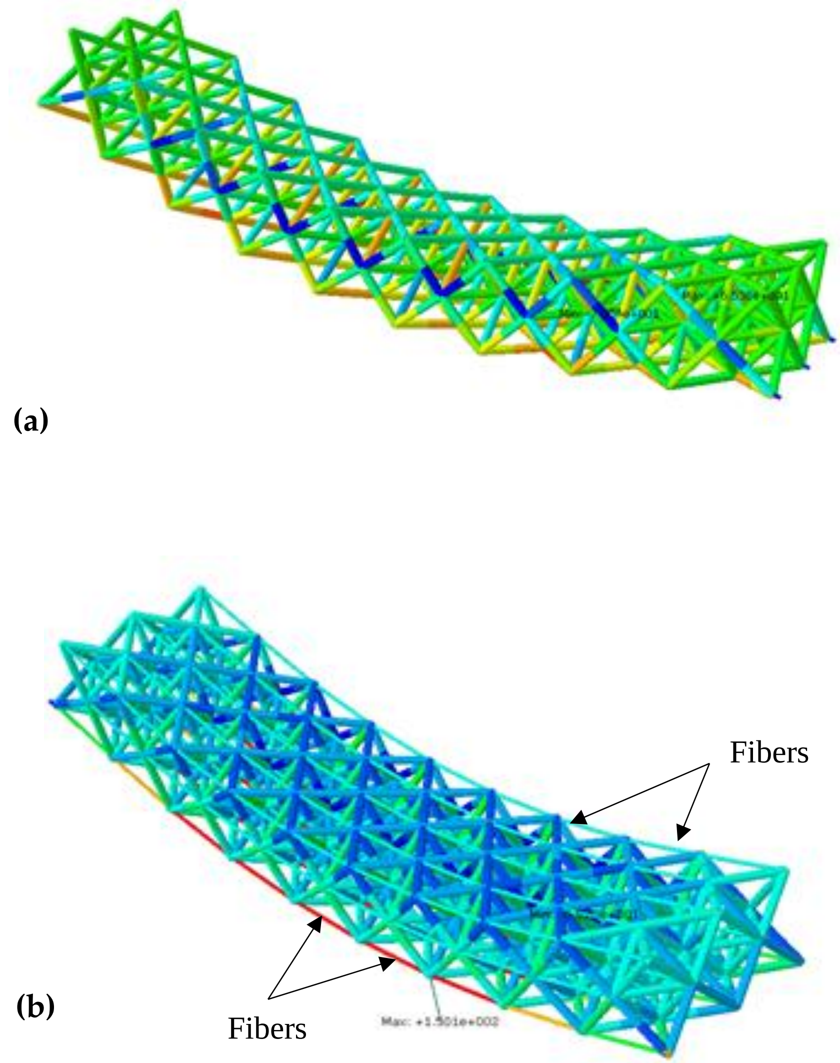
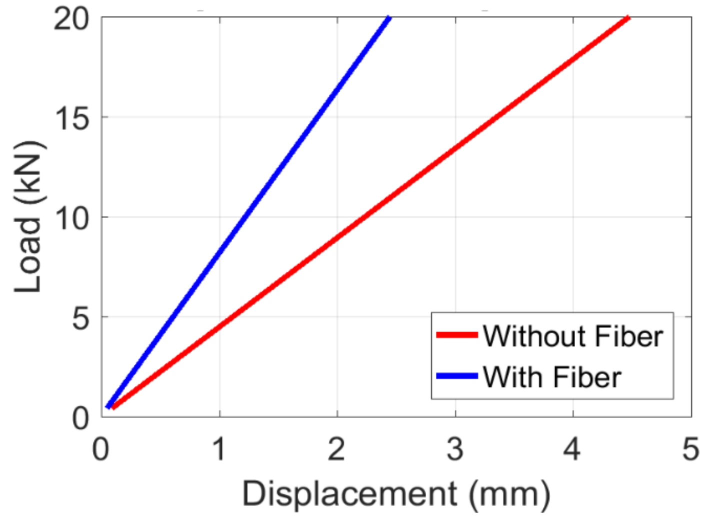


Figure 2-13. (a) Deformed octet structure, (b) Deformed octet structure with steel fibers

Figure 2-14a and Figure **2-14**b represent the displacement at the loading points and maximum stress (S-Mises) observed in structures for parametric loading respectively.

(a)



(b)

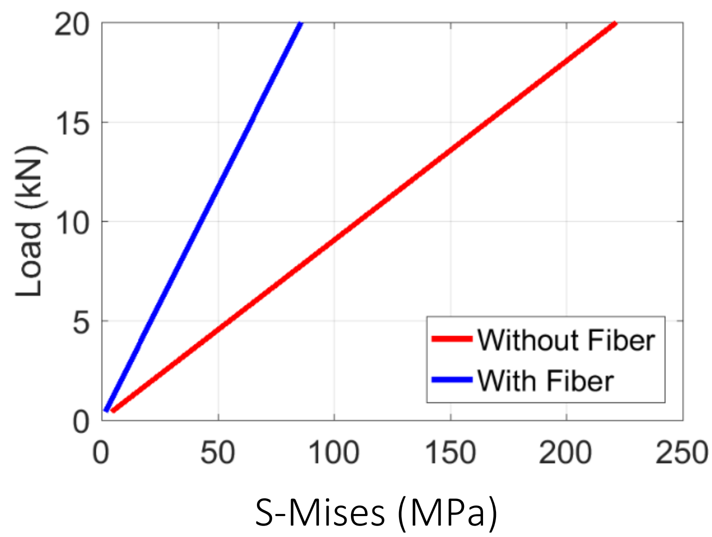


Figure 2-14. (a) Load vs displacement, (b) Load vs stress at loading points

Table 2-2 provides the details of effectiveness of steel wires through displacements and stresses due to the presence of steel wires. The deflection was in the structure with fibers deceased by 2 mm. Increase in strength due steel wires was about 146.1 MPa. This shows that the placement of fibers in between the nodes has been significant in reducing the stresses. The stiffness of the structures has considerably increased under bending loads because of the presence of wires, which are effectively opposing the movement through their tension. Octet structures with fibers were found to have a specific bending stiffness of 6.23 x 10^{12} mm^3/s^2 and octet structures without fibers had 3.93 x 10^{12} mm^3/s^2.

Table 2-2. Effectiveness of fibers

	Maximum Displacement (mm)	**S-Mises Stress (MPa)**
Octet Structure	4.4	221.2
Octet Structure with steel wires	2.4	75.1

The shear stress in both the structures with and without fibers, was studied from the 3D Beam analysis (Section 2.2.4). The decrease in shear stress is shown in Figure 2-15a. The tension experienced in all bottom wires were studied, as shown in Figure 2-15b.

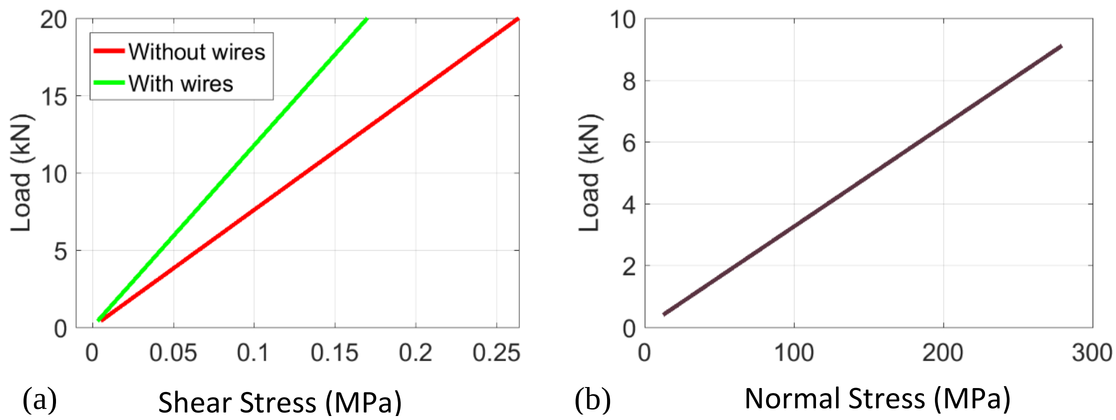


Figure 2-15. (a) Shear stress in octet structure with wires (b) Tension in steel wires

As observed in Figure 2-15, there is presence of shear stress in octet structure with wires, but the value is very low (0.25 MPa). The tension in steel is seen to be increasing with the load. The structure with wires is shown to be stiffer and stronger through results in Table 1. This behavior is typical of tensegrity structures.

2.2.6 Octet Structure – 3D Solid Analysis

3D Solid octet-cellular structure was analyzed to further probe into the mechanics of the structure and compare with the results of beam analysis. The bending stresses occurring in the octet-cellular structure was of main interest in order to prove the tensegrity behavior through the simulation of 4-point bending test. The analysis of 3D solid structure provides a better representation of elements involved in 4-point bending test.

2.2.6.1 Geometry, Mesh, Contact and Boundary Conditions

The geometry of the cellular structure was constructed according to the 3D beam analysis. The diameter and length of the struts remained the same. The geometry was built carefully such that it can be easily partitioned to enable meshing of brick elements as shown in Figure 2-16a. The material properties of the structure were assigned the same as the previous analysis with octet cell as aluminum and fiber being the steel wire. The fiber material was also assigned with no compression elements so that the material engaged only in tension. The boundary conditions of the 4-point bending test were assigned to the loading pins. The bottom pins were fixed completely while the pins on the top surface were moved to apply loads on the top surface as shown in Figure 2-16b. The entire structure was fixed in the out of plane direction to prevent the structure from moving or toppling in any orientation other than the loading direction. The octet structure with fibers is shown in Figure 2-17a and the boundary conditions remained the same.

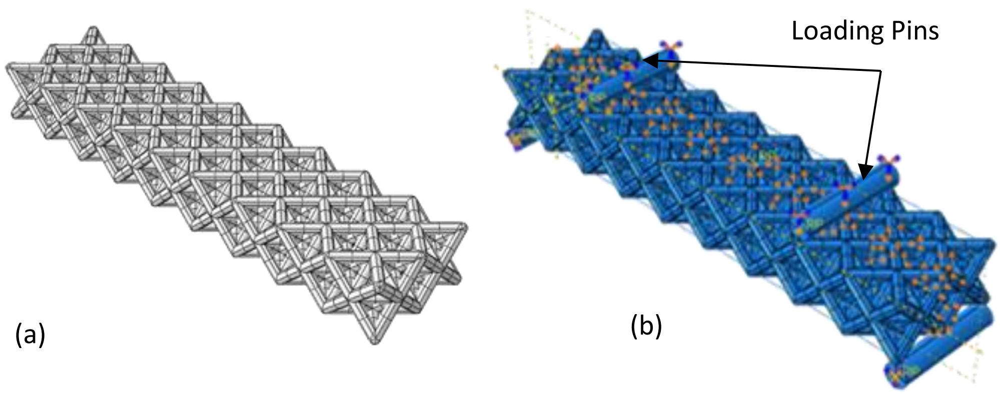


Figure 2-16. (a) 3D Octet Structure (b) Boundary Conditions

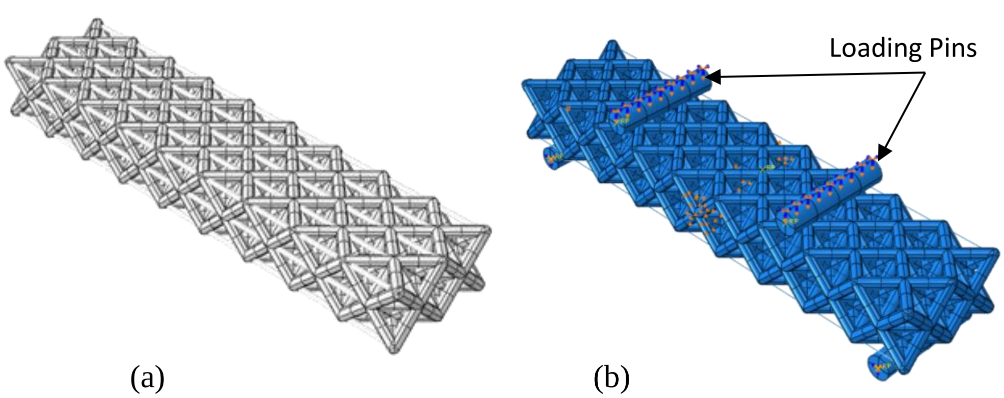


Figure 2-17. a) 3D Octet Structure with steel wires b) Boundary Conditions

Brick elements (C3D8I) were used for meshing the entire structure as shown in Figure 2-18a and Figure **2-18**b. These elements are meant to represent the mechanics accurately for bending load applications. The loading pins for 4-point bending test were accurately modeled based on the testing equipment. The pins were modeled as rigid bodies and were meshed with discrete rigid elements.

The contact between the structure and loading pins was modeled with a nominal frictional co-efficient value of 0.25. This value was tested for sensitivity and the analysis produced a similar result for every trial. The contact was defined only for the top and bottom surface of the structure with the loading pins as master surfaces guiding the movement of nodes in the structures. Finite sliding was defined between the master and slave surfaces.

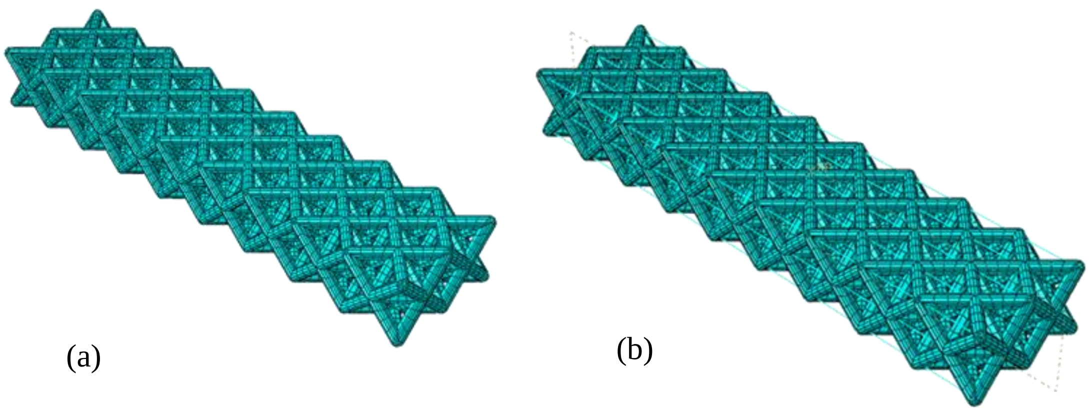
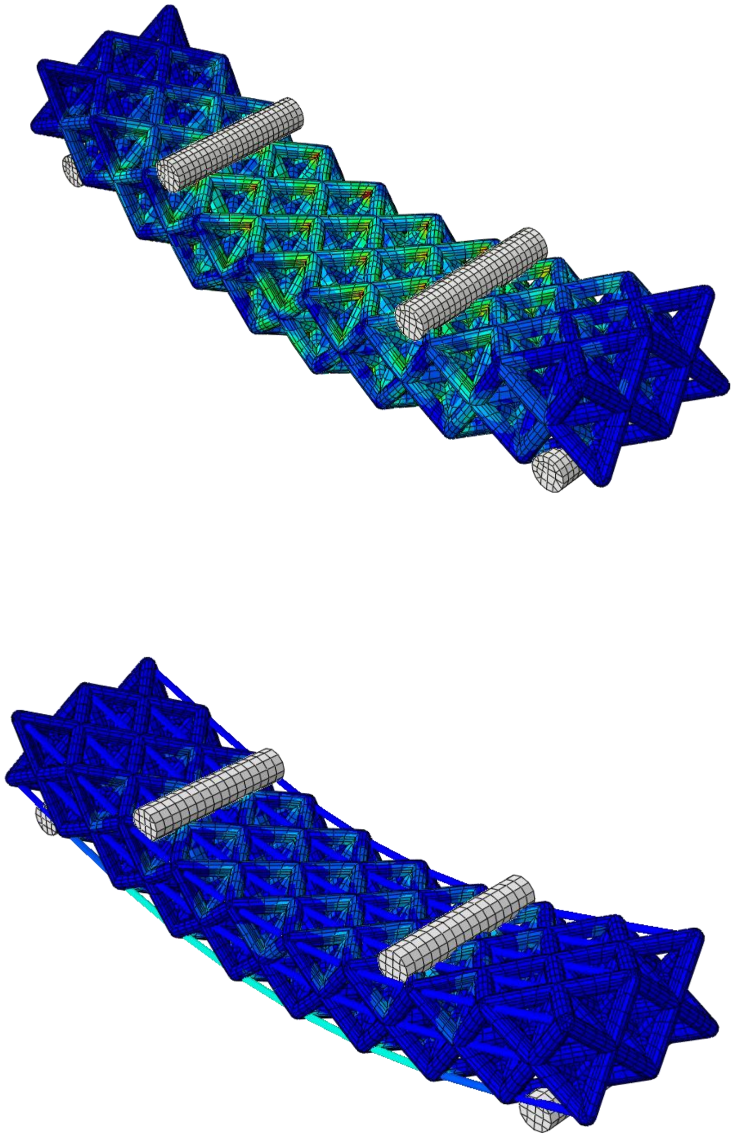


Figure 2-18. 3D Octet Structure – Mesh (a) without fibers (b) with fibers

2.2.7 Results

The deformed structures are indicated in Figure 2-19. The structure was studied for overall strength and bending and the results are presented in the next section. The deformations in both the octet structures were studied in terms of stresses and displacements. The displacements and stresses occurring at the loading points were considered to study the difference between both the structures.

(a)



(b)

Figure 2-19. 3D Octet Structure – Deformed (a) without fibers (b) with fibers

Figure 2-20 represents the displacements occurring in structures, while Figure 2-21 shows the stresses generated in the structure due to the 4-point bending simulation. Observing the slope of both curves in Figure 2-21, it can be noted that the stiffness has significantly increased, similar to the case in 3D beam analysis. Octet structures with fibers were found to have bending stiffness of 6.96 x 10^{12} mm^3/s^2 and octet structures without fibers had 4.03 x 10^{12} mm^3/s^2**.** Also, the strength of the octet structure with steel wires has improved compared to octet structure without fibers.

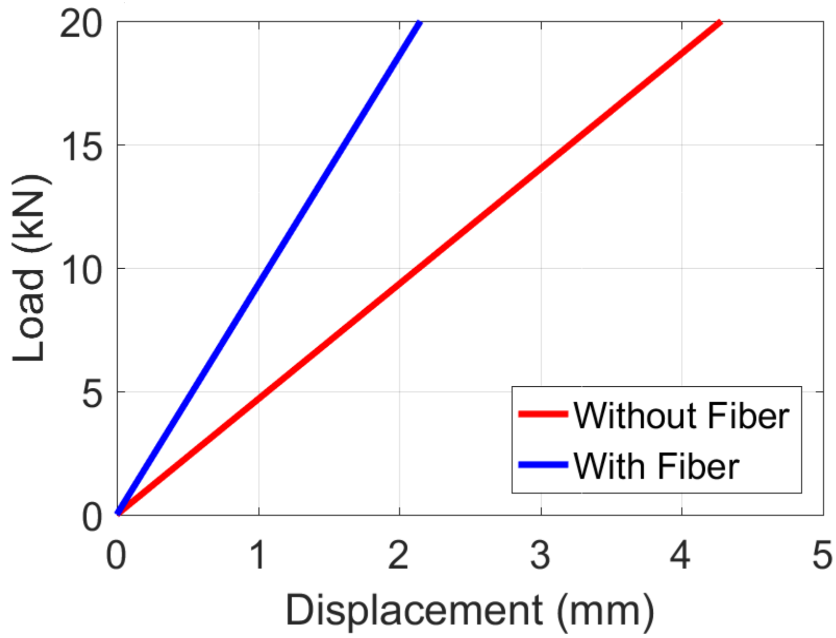


Figure 2-20. Load vs Displacement at center – 3D solid structures

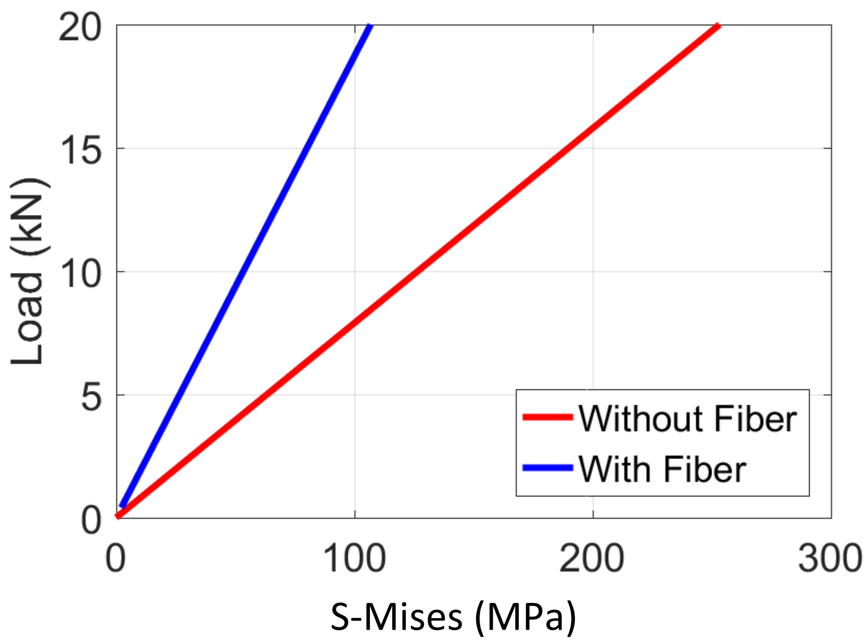


Figure 2-21. Load vs Stress at center – 3D solid structures

The results have been listed in Table 2-3. The maximum displacement in octet structure with steel wires decreased by 2.13 mm at the loading point while the maximum stress reduced by 153.2 MPa. Through this modeling exercise steel fibers have proved to improve the structural performance of octet-cellular structure under bending loads.

Also, these results validate the 3D beam analysis since the stresses and displacements are occurring in the similar range, where displacements of 4.4 mm and 2.4 mm, and stresses of 255.8 MPa and 102.6 MPa were estimated in the previous analysis and it is expected of the beam analysis to predict the overall strength and stiffness accurately.

Table 2-3. Displacements and stresses

	Maximum Displacement (mm)	**S-Mises Stress (MPa)**
Octet Structure	4.28	255.8
Octet Structure with steel wires	2.15	102.6

The sensitivity of mesh for both the structures was studied. The number of elements was varied from 41596 to 64528 and Von Mises stress was considered. The stresses at center of the structures for different meshing schemes are shown in Figure 2-22. The mesh convergence for octet structure without fibers is 1.42 % and for octet structure with fibers it is 1.56 %, as shown in Figure 2-22.

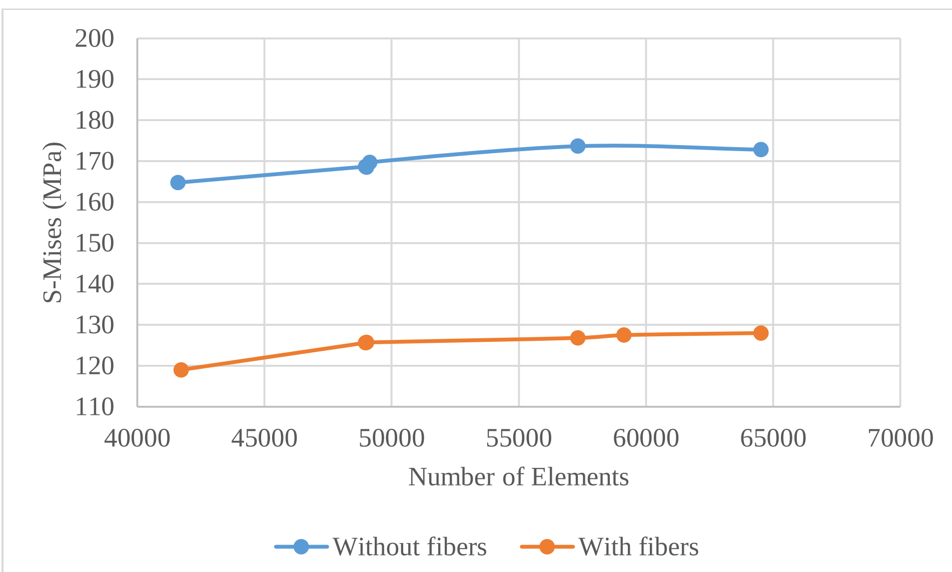


Figure 2-22. Mesh Convergence Study

2.2.8 Discussion

The 2D finite element analysis provided a good basis for placement of fibers such that they were engaged in tension. Through understanding the apparent movement of nodes it was clear as to where the fibers would be more efficient. As this concept was applied to the octet beam and solid structure, the octet-wire arrangement proved to increase the stiffness and strength of the structure. Again the fibers were placed in the nodes of the unit cell. This is comparable to the tensegrity structures from a structural aspect where the strings are present at the nodes.

A section of a strut, as represented in Figure 2-23, was probed to measure the value of bending stress occurring in the structure. The location of this strut was at the center of the structure, where high bending stresses were observed. Under bending loads, the top surface of the strut undergoes compression while the bottom surface experiences tension. The compressive and tensile stresses were noted from the analysis at the cross-sectional points. These stresses collectively provide the bending stress occurring at that cross-section.

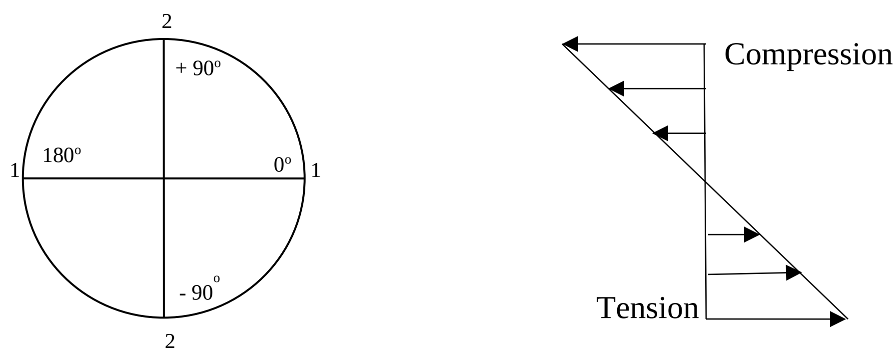


Figure 2-23. Cross-sectional points for bending

Table 2-4 indicates the values of maximum bending stresses occurring in a section of strut. The compressive stresses are indicated with (–ve) sign while (+ve) sign is used for tensile stresses

Table 2-4. Bending Stresses - 3D solid

Section Point	Octet structure - Bending Stress (MPa)	Octet structure with fibers - Bending stress (MPa)
+90°	- 60.71 MPa	- 6.5 MPa
-90°	+ 62.9 MPa	+ 5 MPa

There is a reduction of bending stresses in octet structure with wires. This is attributed to the interplay between octet cellular shape and the tension in steel wires. Compared to normal stress regimes acting in the structure, the bending stress is very low. Therefore, this arrangement showcases tensegrity behavior. As a consequence of tensegrity behavior where the tension in wires can effectively engage to reduce the stress due to the shape of the cell and wire arrangement. Since there is low presence of bending stress, it can be called as nearly tensegrity behavior.

2.3 Design Criteria

The 3D beam analysis, as shown in Section 2.2.4, provided results to predict the decrease in maximum stresses occurring in the structures. Following the same steps, it is possible to analyze the variations in performance based on the dimensions and materials properties. To provide a basis for choosing the dimensions of truss and fiber based on material properties, parametric FEA modeling was conducted. The maximum stress (S-Mises) present in the structure was taken into consideration for providing this basis, and parametric modeling was conducted on the octet-cellular structure with steel wires keeping the same boundary conditions as Section 2.2.6 for 4 point bending test.

This analysis presents results for a designer to decide on the design variables, as listed in Table 2-5, while the material properties of the cellular structure and fiber are known.

Table 2-5. Design variables in parametric modeling.

Fixed Parameters	Design Variables
Strut - Material	Strut Length
Fiber - Material	Strut Diameter
Number of Repeating Cells	Fiber Diameter
	Overall Size

This study enables a designer to decide on the overall the size of the structure, strut and fiber diameters when Young's Modulus of fiber is known. The same method can be followed for any other fiber material. The analysis parameters can also be switched such that the Young's Modulus of the material can be found. The main aim of this study is to show that the structures produced can be tuned for specific strength and stiffness based on the application requirement.

2.3.1 Parametric Model

The octet structure built in Section 2.2.6 was chosen as an example for this study. The material properties of cellular structure and fiber remained the same as used in Section 2.2.4 (i.e., octet-cellular – aluminum, fiber – steel wire). The number of cells remained the same with nine octet cells in length and two in the width.

For the parametric modeling, the strut length, diameter and fiber diameter were varied and the maximum stress in each of the situation was considered. It is important to note that overall size, although it's a design variable, it is dependent on the strut length since the number of cells are fixed. Therefore, the parameter that were varied in this study are strut length, strut diameter and fiber diameter.

A MATLAB program was coded to build the coordinate points of the octet structures based on the different lengths of struts. Using the length of the strut in an octet structure the entire coordinate can be built because of the tetrahedron shape, which is symmetrical in all directions. The strut lengths chosen for this study as examples are 22.5 mm, 25 mm and 30 mm.

The resulting coordinate points of the octet cellular structure were directly integrated in the input file generated for the analysis in Section 2.2.6. The input file generation with different coordinate points was automated with strut and fiber diameters indicated as free parameters. A Python script was programed to assign the varying parameters for strut and fiber diameters. The strut diameter was varied from 6.25 mm to 9 mm while the fiber diameter was varied from 2mm to 5 mm. Every length of strut had a script assigned to it with the same parameters. These python scripts were executed directly in the ABAQUS program and the results were gathered.

2.3.2 Results

The S-Mises stresses from all the analysis runs were collected and graphs were generated for every strut-length. Strut lengths of 22.5 mm, 25 mm and 30 mm are presented here in this study and the respective results are indicated from Figure 2-24 - Figure **2-26**.

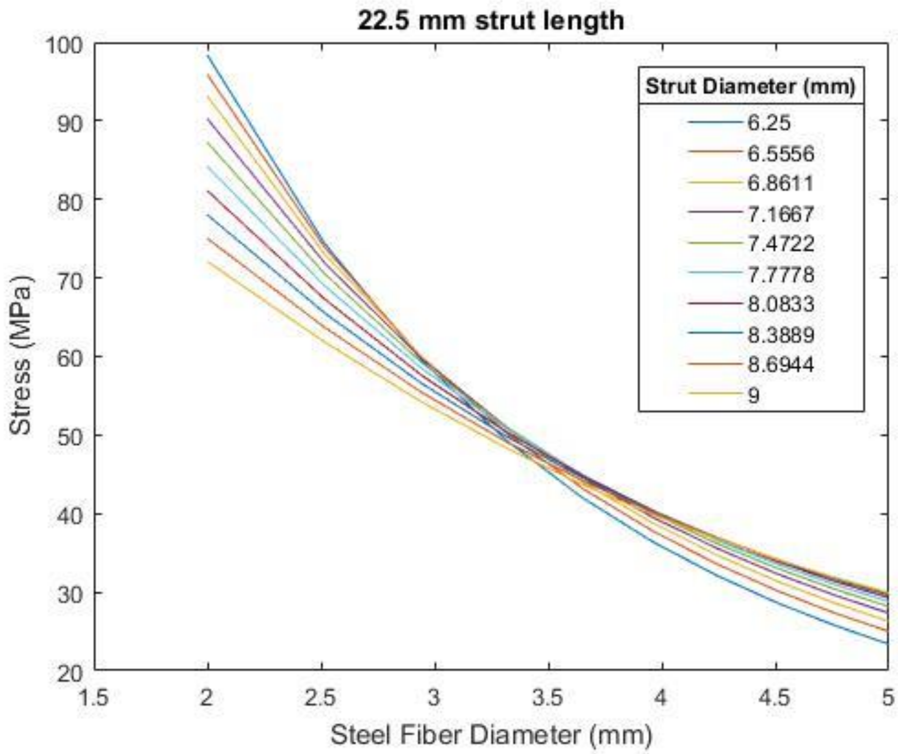


Figure 2-24. Design Curve – Strut Length - 22.5 mm

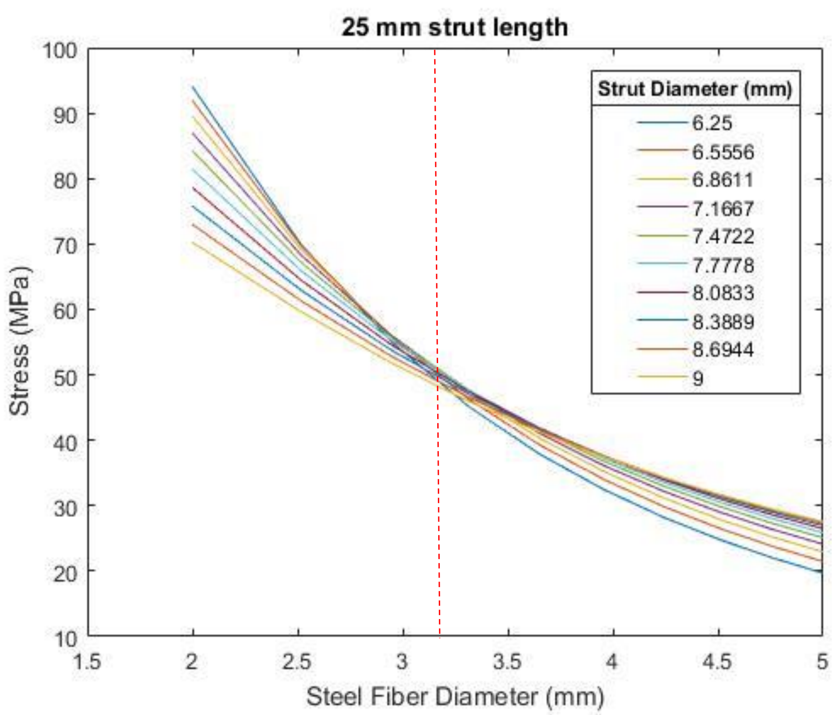


Figure 2-25. Design Curve – Strut Length - 25 mm

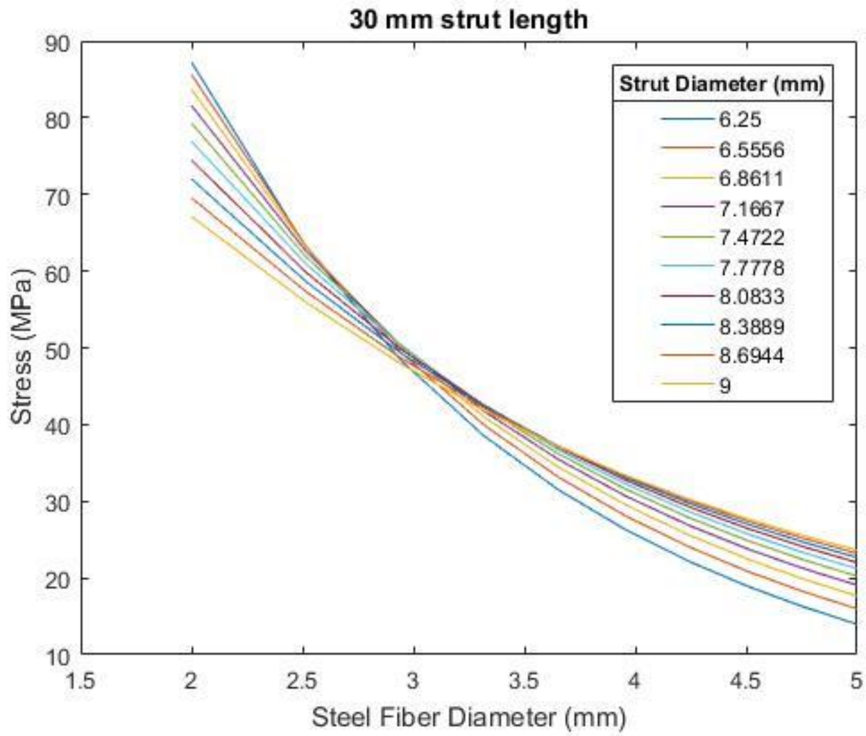


Figure 2-26. Design Curve – Strut Length - 30 mm

It can be observed from the graphs that as the fiber diameter increases, the stress in the overall structure decreases. Specific diameter size can be chosen to arrest the stress to a particular value. This in turn gives a good control of tailoring structure for a specific strength and stiffness. For example in Figure 2-25, for a 25 mm long octet-strut, steel fiber diameter of 3.25 mm decreases the stress to 50 MPa. Also, above a value for fiber diameter, the stress value reaches a constant value. This is primarily because the fiber-diameter tends to be closer to the size of the strut diameter and dominates over the octet structure. Using this analysis, optimal fiber size can be chosen for the structure and avoid unwanted addition of material. This study can be extended to any size of strut and material properties to obtain similar results. Through those results appropriate fiber diameter can be selected.

Also, a response surface, as shown in Figure 2-27, was studied for the strut length 25 mm. The decrease in stress due to the variation of the fiber diameter dominates the variation of strut diameter. The variation of strut diameter caused a decrease in stress of 2.85 MPa/mm while the variation of fiber diameter caused a decrease of 28 MPa/mm. It is more efficient to increase strength of the structure through variation of fiber diameter and also the increase in weight is minimized if fibers with high specific modulus values are used.

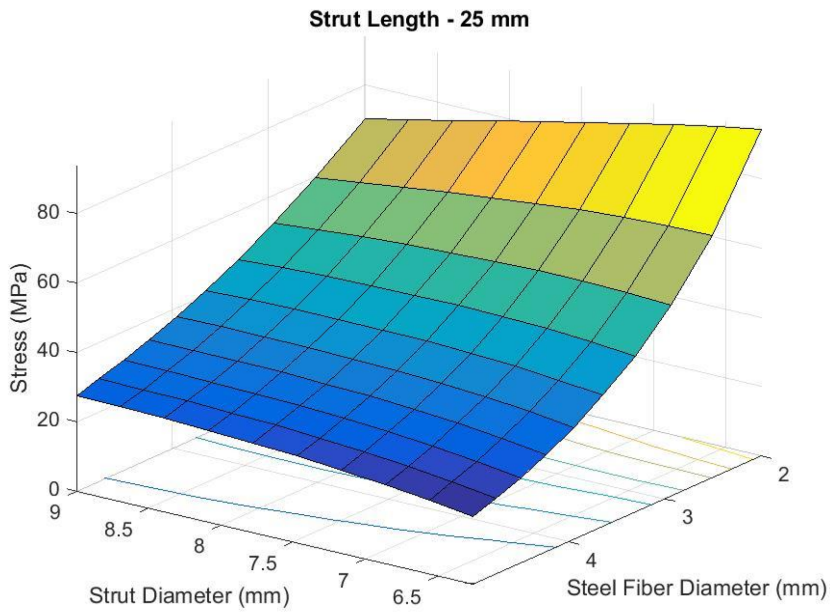


Figure 2-27. Response surface for strut length - 25mm

2.4 Closure

The design steps in establishing tensegrity behavior in cellular structures was presented. 2-D finite element analysis of 4-point bending test was conducted on a truss-arrangement to understand the mechanics and identify the placement of fibers in Section 2.2.2. 3-D beam and solid analysis of octet structures with fibers showed improvements in strength and stiffness due to incorporation of tensegrity behavior (Section 2.2.5). The presented analysis technique can be effectively used to include tensegrity behavior in other cellular materials. The bending stresses in octet structures decreased, while wires engaged in tension to reduce stresses indicating nearly tensegrity behavior was achieved (Section 2.2.8).

The fibers effectively reduced the stress from adjacent sections by engaging in tension. A manufacturing process for embedding steel fibers in aluminum octet structures was presented, where Binder Jetting is combined with metal casting. The structures without wires experienced a maximum stress of about 253.4 MPa while the structures with wires reported stress of about 75.1 MPa (Table 2-2). In the analysis it was seen that octet structures with fibers experienced very little bending stress (about 0.25 MPa). Through 3D solid analysis, the bending stresses were shown to decrease by 66.66% in octet structures with fibers. This was attributed to the tensegrity behavior introduced due to the presence of fibers. This nearly tensegrity behavior improved strength and stiffness during 4-point bending test, as discussed in Section 2.2.7. Design criteria to control and tune the octet-fiber structures was established so that optimal fiber sizes can be selected through parametric modeling (Section 2.3). The method is applicable to any strut size and material property. It was shown that variation of fiber diameter is more efficient to increase strength.

This research faced limitations while completing the work. In the 3D solid model, high contact stresses were present at nodes underneath the loading points (Section 2.2.6). In future, better contact model needs to be developed to represent the sliding between loading pins and the structure. The bonding between the fiber and cellular material assume perfect locking; however, this is not a true representation. Future models should accommodate sliding to predict more accurate results. The selection of locations to place fibers can be improved by using topology optimization, minimizing the deflection and bending stresses.

3 FABRICATION AND TESTING OF CELLULAR STRUCTURES WITH TENSEGRITY BEHAVIOR

Abstract

Tensegrity arrangements offer high strength and stiffness for low mass. However, the complexity of these structures pose manufacturing challenges, limiting the applications. This research looks to Additive Manufacturing (AM) as a means to introduce tensegrity behavior in cellular structures through the use of long continuous fibers. By combining Binder Jetting and metal casting a controlled reliable process is shown to produce aluminum octet-cellular structures with embedded fibers. 3D-printed sand molds embedded with long continuous fibers were used for metal casting. The fabricated structures were then subjected to 4-point bending tests to evaluate the effects of tensegrity behavior on the cellular mechanics. Through this fabrication and testing process, this work addresses the gap of evaluating the performance of tensegrity behavior. The overall strength increase by 30%. The interface between the fiber and metal was investigated using an EDX study. The simulation and experimental results were then compared to show the predictability of this process with errors of 2% for octet structures without fibers and 6% for octet structures with fibers.

3.1 Introduction

3.1.1 Cellular Structures with Continuous Fiber-Reinforcement

Cellular structures provide high strength, high stiffness for a low mass density [2], [33]. In addition, cellular structures offer enhanced energy absorption, thermal and acoustic insulation [3]. Cellular metal structures have potential applications in aerospace, construction, ship-building, automotive and sporting equipment due to their high strength and stiffness along with low density [3]. Due to the superior performance of periodic cellular structures, recent cellular material research has been focused to improve the design and strength of periodic cellular topology and thereby increase the overall strength of the structure [21, 28]. The structural limitations of cellular structures include failures caused due to indentation weakness [2], low elastic moduli [33], and compressive stresses [34]. It is reported that the core of the cellular structure undergo local yield or crushing [28, 35], [29]. The strength of the core and cell size limit the overall strength of the cellular structure [36].

In view of enhancing structural performance of cellular structures, one such solution is through introduction of tensegrity behavior in cellular structures. In Chapter 2, the design steps to introducing tensegrity behavior in octet-cellular structure mechanics through continuous long fibers was shown. Under bending loads the deflection was shown to decrease by 2 mm while stresses decreased by 120 MPa. However, fabricating these structures is challenging. The process needs to avail selective placement of long continuous fibers in complex cellular geometries, and produce homogenous and isotropic parts. The complex internal geometry of cellular structures are not possible to be made via traditional subtractive machining.

3.1.2 Manufacturing: Fiber-Reinforced Periodic Cellular Structures

While joining techniques have been used to create periodic cellular structures [5], these processes include complex and expensive customized fixtures to produce the parts.

Previous studies on composite cellular structures have all concentrated on short fiber-reinforcement directly in the material of the strut [21] [31-36]. For example, Ti–6Al–4V-coated SiC monofilaments were used to fabricate square cellular lattice structures [21], [22], as shown in Figure 3-1. Fiber Reinforcement in titanium square lattice [21]. To produce square lattice structures, the process employs physical vapor deposition of metal on fibers, fixtures to assemble mono-filaments and diffusion bonding in a vacuum furnace to form structures.

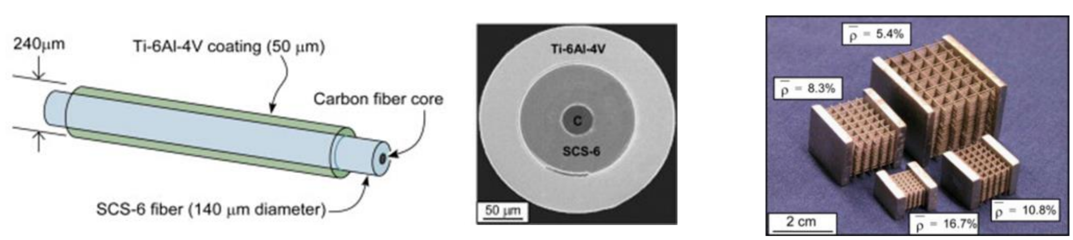


Figure 3-1. Fiber Reinforcement in titanium square lattice [21]

These processes are bound by usage of expensive fixtures, instruments and complex procedures. They are constrained in creating more intricate shapes due to the inability in making complex fixtures. Consequently, selective fiber placement, as required for the designs from Chapter 2, is not possible due to the complexity involved in creating the fixtures. Hence, this research, seeks a solution through AM to fabricate the designed structures.

3.1.3 AM of Cellular Structures: Powder Bed Fusion

AM has mainly facilitated the current research effort of producing designed mesostructures by providing superior degree of freedom in terms of design and material placement, and improved processing controls. Powder bed fusion AM processes can be used to produce complex metal parts. Research efforts towards fabricating metal cellular structures have all been directed through the use of Electron Beam Melting [45], Selective Laser Melting [46] and Direct Metal Laser Sintering[47] processes. For example, periodic cellular structures were created using AlSi10Mg material with direct metal laser sintering [48]. The resultant parts showed good geometric agreement with designed models and predictable compressive modulus was achieved.

Direct metal AM processes have been able to create parts with complex geometries with predictable properties; however, certain limitations exist. These processes are limited by the set of working materials available to process. Another constraint is posed due to the warping of the printing parts primarily caused by the residual stresses, which are imposed by rapid solidification of melt during the energy scan [49], [50]. The presence of anchors limits the realization of the actual design, and causes increase in production time and cost [51]. The anchors need to be machined to get the final parts, thus, reducing the design space especially for large parts. Finally, the current processes are not capable to fabricate large scale cellular structures, as the largest build box commercially available is 40 cm x 40 cm x 40 cm.

3.1.4 Goal and Roadmap

While AM techniques have produced cellular structures with designed mesostructures, they are not equipped for embedding of fibers. Hence, there is a need to develop a process for fabrication of cellular structures with tensegrity behavior. **The goals of this work are to realize a process to embed long continuous fibers in cellular structures based on the design shown in Chapter 2, and to evaluate the bending**

performance of the fabricated structures through testing and characterization, and compare the simulation and experimental results.

The process presented in this work uses AM to address the intricacies involved in fabricating tensegrity structures and the limitations of traditional manufacturing techniques in fiber-reinforcement. In this work, the layer-by-layer build approach of AM is leveraged to selectively place long continuous fibers to produce tensegrity behavior in cellular structures. The process presented in this work is shown to include the long continuous fibers at the desired locations in the complex cellular sand molds printed using Binder Jetting and then metal is cast to fabricate the designed octet-cellular structures with tensegrity behavior. The resultant parts from this process were subjected to 4-point bending test and evaluated for their overall strength.

Section 3.2 will discuss the research efforts in using AM and metal casting to produce cellular structures. Section 3.2.2 explains the prior work in Binder Jetting and metal casting process. Section 3.3 details the process chain and the modifications required to create the structures, and experimental methods. 4-point bending test was conducted to evaluate the overall strength of the fabricated structures. The overall strength of the octet structures with and without fibers were compared to show the effectiveness of the tensegrity behavior in Section 3.3.2. The characterization of the interface is provided to study the bonding between the fibers and octet cellular structure (Section 3.3.2.2). In addition, the experimental results were compared with modeling solutions to show the predictability of the structures fabricated using the process presented in this work. Section 3.4 provides the closure and future work.

3.2 AM + Metal Casting Hybrid Processes: Cellular Structures

3.2.1 AM and Investment Casting

Hybrid processes have been formulated to address the design limitations of traditional casting through use of AM techniques for creating complex patterns. Polymer patterns fabricated through AM techniques are used to create ceramic molds and then metal is cast to gain the final part. Investment casting process was carried out using truss patterns printed through material extrusion AM process [29]. The patterns were printed using acrylonitrile–butadiene–styrene (ABS) material and ceramic molds were created around these pattern. The ABS was burnt out to make space for the cast metal to fill the mold as shown in Figure 3-2.

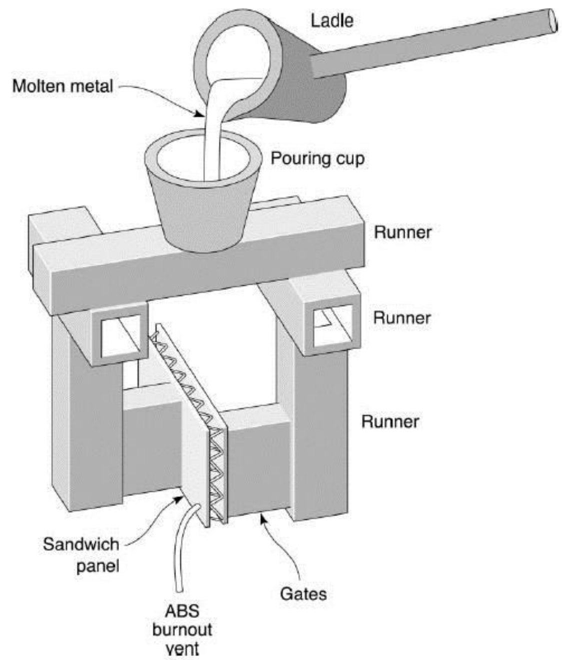


Figure 3-2. Investing Casting using ABS pattern [29]

Fused deposition of ceramics (FDC) has been used to directly create ceramic molds through slurry infiltration of porous polymer molds and then used for casting of metals [52]. Material Jetting AM was used to create patterns and lost wax casting was undertaken to produce complex heat sink designs [53].

These hybrid processes have shown to create parts with complex geometries; however, these methods impose certain limitations. The hybrid processes depend on AM to create patterns, which are bound by a small build volume. This causes an issue of scalability of parts [54], and most of the processes have only shown to create single build layer. Cracking of molds due to the burnout of pattern materials is another limitation of this process [55]. Most of the materials used for patterning through AM are typically not well suited for burnout process since their thermal expansion is higher than traditional wax. Finally, the coated ceramic slurry is difficult to remove once the casting of complex shapes is done [56], which limits the design of cellular topology. The residual material can be removed by chemical leaching process, but this comes at a higher cost.

Hybrid AM and investment casting process can be used to produce the structures designed in this work; however, the process would demand a careful coating of the patterns such that fibers are not in contact with ceramic slurry. This would considerably increase the time and cost involved. Hence, this work looks to Binder Jetting and metal casting process to address the aforementioned challenges.

3.2.2 Binder Jetting AM and Metal Casting

Binder Jetting is an AM technology where an inkjet head selectively deposits binding agent on a layer of powdered particles in an assigned specific path. After a layer is patterned, the build piston is lowered and another layer of powder is spread by the roller. Again the binding agent is deposited based on the pattern, and subsequent layers are bound by the jetted binder. The schematic of the process is shown in Figure 3-3.

In traditional casting techniques it is not possible to make complex sand molds with intricate geometries. Binder Jetting can pattern foundry sand to fabricate complex sand molds for metal casting. Cellular structures geometries can be fabricated using this process [23]. The complex molds can be designed with integrated gating systems, runners and downsprue eliminating the need for pattern tooling and the associated costs.

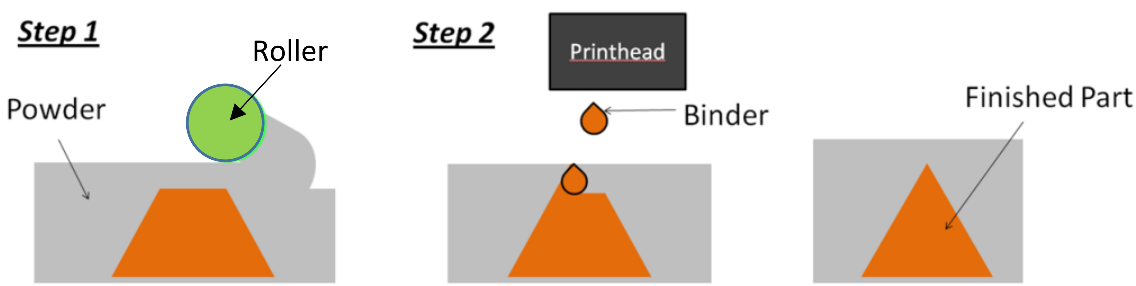


Figure 3-3. Schematic of Binder Jetting AM Process

The manufacturing process to produce complex cellular metal composites using Binder Jetting AM process and metal casting was devised and octet cellular structures were fabricated and evaluated for their compressive and impact strength [23] [57]. Further, the process study was completed with investigations on the effects of printed mold on metal castings[58] and binder burnout characteristics to mitigate gas defects in the castings [59]. The resolution constraints of printing process and manufacturing constraints were also identified [57].

The process chain established by the previous study [23] is shown in Figure 3-4. Sand molds are printed through Binder Jetting process using digital mold designs and metal is cast into these molds to create the desired part. The digital mold model of the complex cellular geometries was first created. The molds were then printed using Binder Jetting. Metal was cast to realize the final desired part. Using this process, a designed mesostructure can be realized, which is not possible using traditional casting techniques.

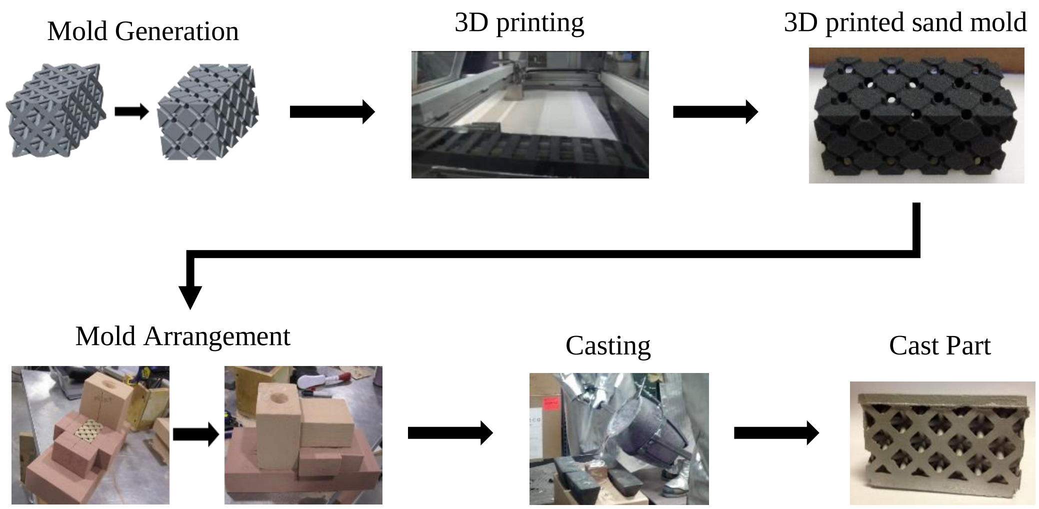


Figure 3-4. Binder Jetting and Metal Casting Process

3.2.2.1 Embedding in Binder Jetting

In addition, Binder Jetting enables embedding of foreign components while printing without affecting the designed mesostructures. Metal-ceramic composite lattice structures were produced using Binder Jetting and metal casting and tested for better energy absorption [60]. Ceramic tiles were specifically located in sand molds printed using Binder Jetting and then metal was cast to create the composite lattice structures. The goal of this work is to expand the ceramic tile embedding effort such that fibers can be selectively placed in cellular structures.

Binder Jetting process has a relatively shorter build time compared to direct metal AM processes due to the presence of 2D material deposition. Larger parts than the build volume can still be fabricated by using modular parts and assembling them to build the final part. Mold designs can be modified and channels can be made to accommodate fibers and placed exactly according to the user requirement. The pins required for aligning mold assembly can be included in the designs and printed. This process provides wide range of materials to select. Any metal that is castable can be used for fabricating the parts. This also gives the freedom for grain-refinement of metals before casting.

Therefore, a combination of Binder Jetting and metal casting techniques will provide the design space to fabricate cellular structures with selective placement of fibers while resolving the issues of material selection. The resultant parts will have isotropic properties, which makes it easier to analyze the performance of the structures.

3.3 Process Overview and Experimental Methods

3.3.1 Process Overview

The process chain of Binder Jetting AM and metal casting to manufacture cellular structures with long continuous fibers is shown in Figure 3-5. The process chain involves the following steps in order to achieve embedding:

a. *Digital Mold Generation:* A octet cellular structure with fiber was designed using a CAD software. Using Boolean subtraction of this model from a block with same overall dimensions, the sand mold design was created.
b. *Split Mold Generation:* The CAD model of sand mold was now split to allow embedding. Grooves were provided on the split molds to accommodate fibers. Pin locators were designed to help in assembling of molds.
c. *3D Printing and Cleaning Printed Molds:* The split mold designs were printed using a Binder Jetting system in a controlled environment to produce desired sand molds. The support material was vacuum cleaned.
d. *Mold and Fiber Arrangement:* The long fibers were placed in the grooves of 3D printed sand molds and held in tension. The molds were assembled with a downsprue and a channel for the metal to flow and fill.
e. *Metal Casting:* Molten A356 alloy material was poured into the mold to produce metal cellular structures with embedded long continuous fibers. The downsprue and channel were machined out to achieve the final desired part.

In this work, the cellular structure was cast with A356 alloy material while 1/8 inch diameter braided steel wires were used as fibers. The reason for choosing braided steel was based on a compatibility study between fibers and A356 alloy material. The tensile strength and stiffness were increased due to the presence of braided steel wires (Appendix A). The procedure, as shown in Figure 3-5, can be followed to embed fibers in any other desired location with different cell geometries. The following sections explain the technical details of the process.

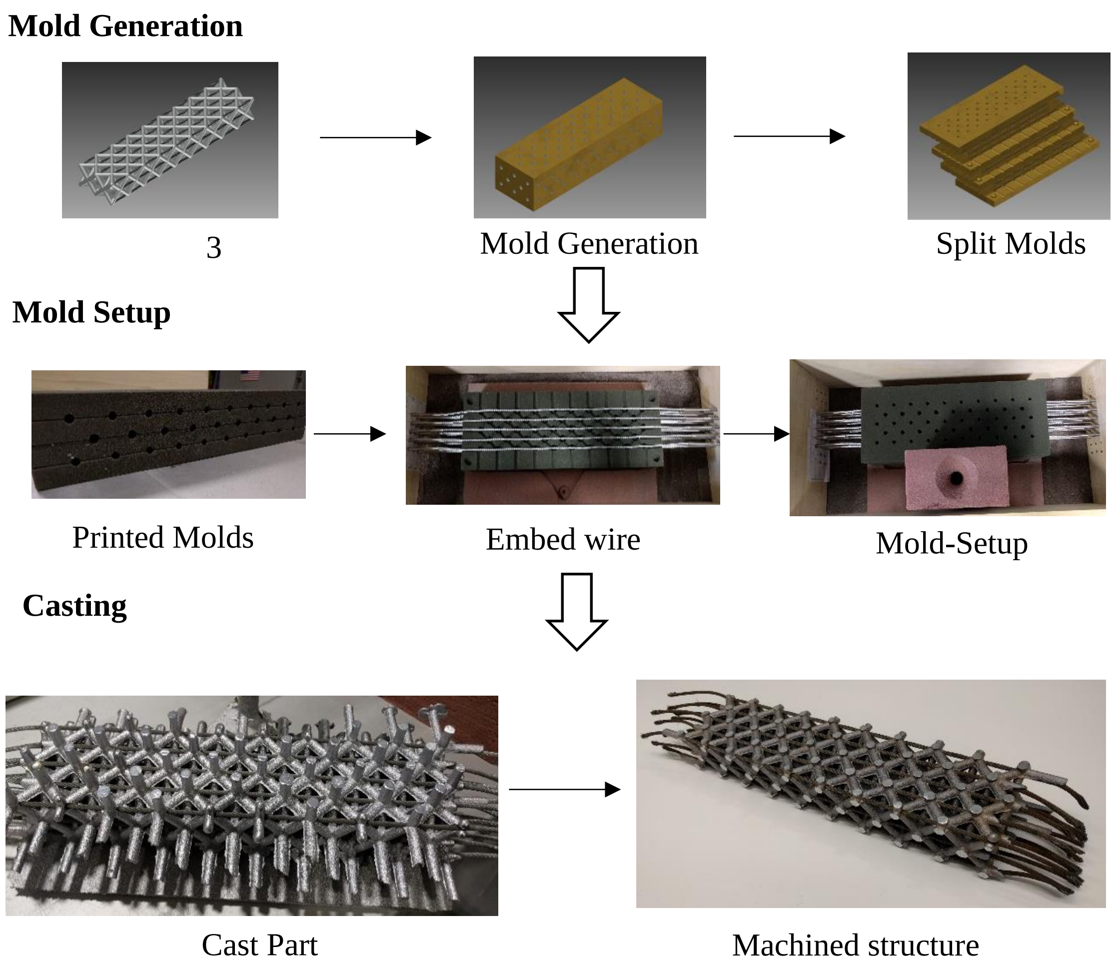
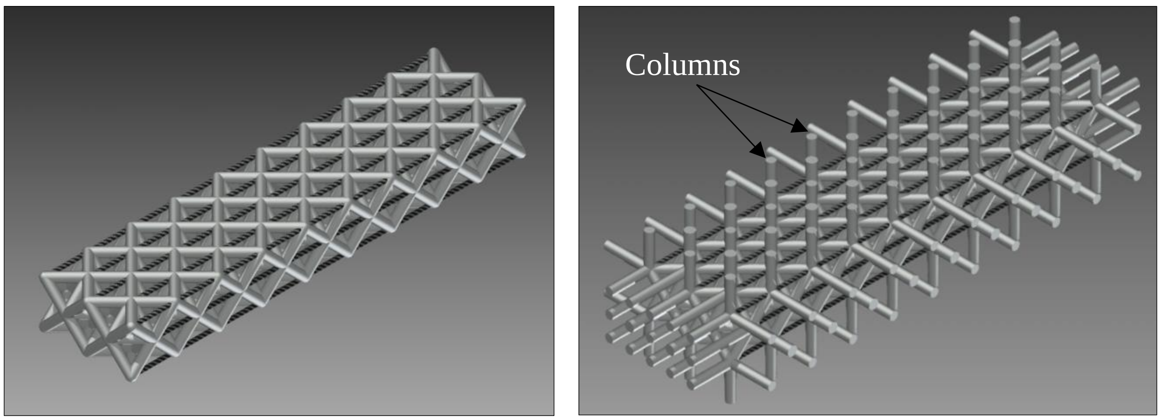


Figure 3-5. Process Chain for embedding fibers in Binder Jetting and metal casting

3.3.1.1 Digital Mold Generation

The octet cellular structure with fibers was designed using a CAD software with exact dimensions of struts and overall size as analyzed in Section 2.2.4 (Figure 3-6a). The strut diameter was 7 mm and the length was 25 mm. The diameter of fiber was 3.175 mm. An octet unit cell was first created and then repeated along desired directions to attain the overall size. Columns of length 25 mm were then projected at nodes on all the faces of the structure, as shown in Figure 3-6b, to facilitate comfortable machining of part. These columns also act as channels for the metals to flow to ensure complete filling of the mold. The overall size of the design was 387.141 mm x 143.355 mm x 81.35 mm.



(a) (b)

Figure 3-6. Digital model of a) octet cellular structure with fibers b) octet cellular structure with extended columns to allow metal flow

To create the desired shape, the mold design needs to be the inverse of the designed structure. The designed structure with columns was subjected to Boolean subtraction from a prismatic solid with the same overall dimensions (387.141 mm x 143.355 mm x 81.35 mm) to generate the mold design as shown in Figure 3-7a. This design was further split into four parts so that fibers could be embedded in the mold arrangement as shown Figure 3-7b. The Boolean subtraction creates grooves in places where fibers are present and the mold was split such that these grooves were divided into two halves as shown in Figure 3-7b. Also, pin locators were designed on all the split molds as indicated in Figure 3-7c to assemble the molds accurately.

A similar procedure was carried out to create mold design for the octet structure without fibers. The design was only split at mid-point to ensure complete cleaning of the mold after printing. The overall size of the mold for both the designs was 387.141 mm x 143.355 mm x 81.35 mm.

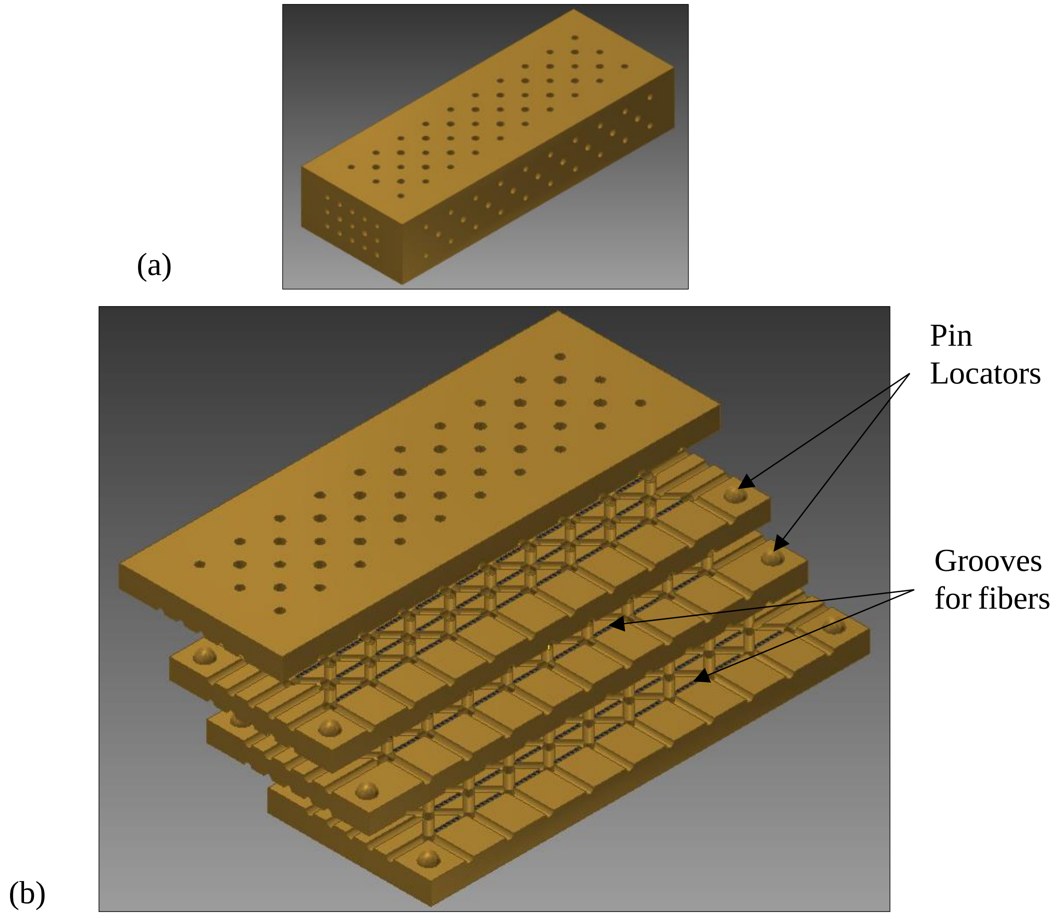
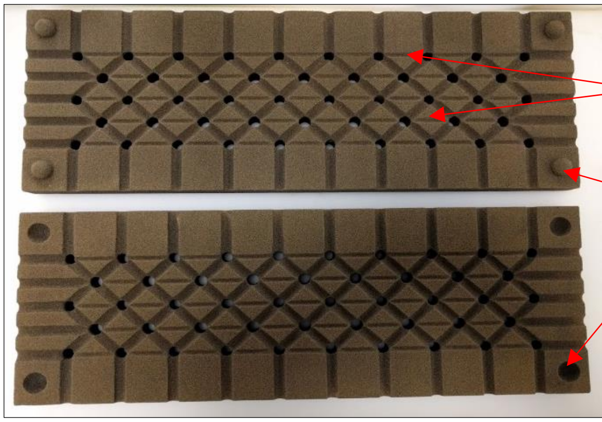


Figure 3-7. (a) Mold design (b) Split mold design – assembly

3.3.1.2 Mold Fabrication

The molds were printed using ExOne S-print machine with refined coated silica sand and required no thermal curing cycle. To produce repeatable properties in the printed parts, the temperature and humidity of printing chamber is controlled. Once the printing is finished, the powder present as the support material inside the structure was vacuum cleaned. The final printed mold structures are shown in Figure 3-8.

a)



b)

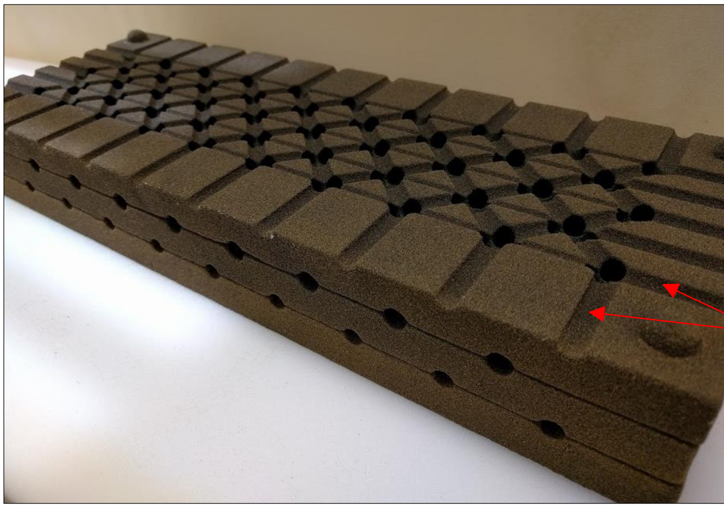
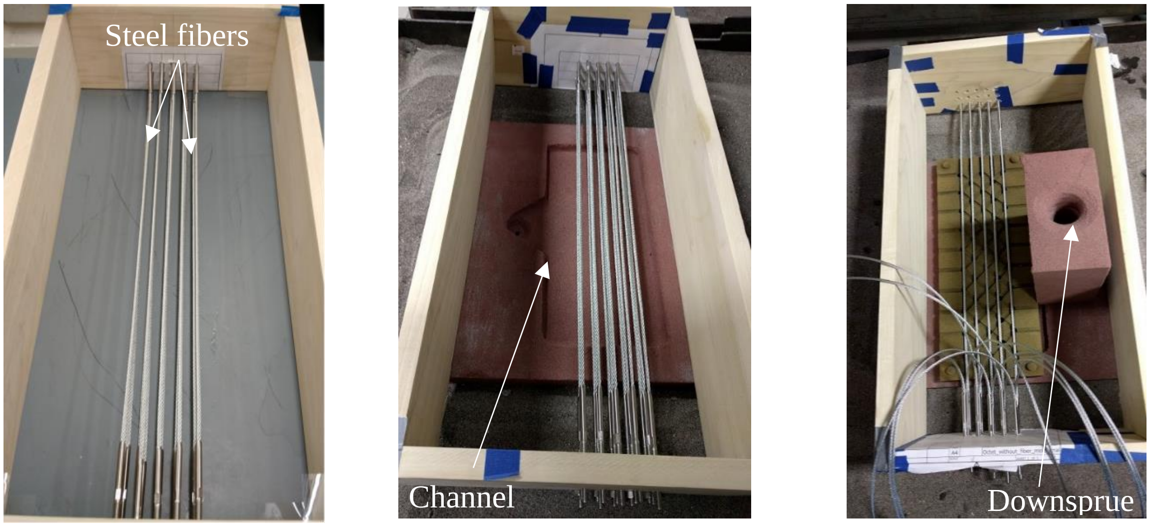


Figure 3-8. 3D printed sand molds (a) Split molds (b) Split mold assembly

3.3.1.3 Mold Construction and Fiber Embedding

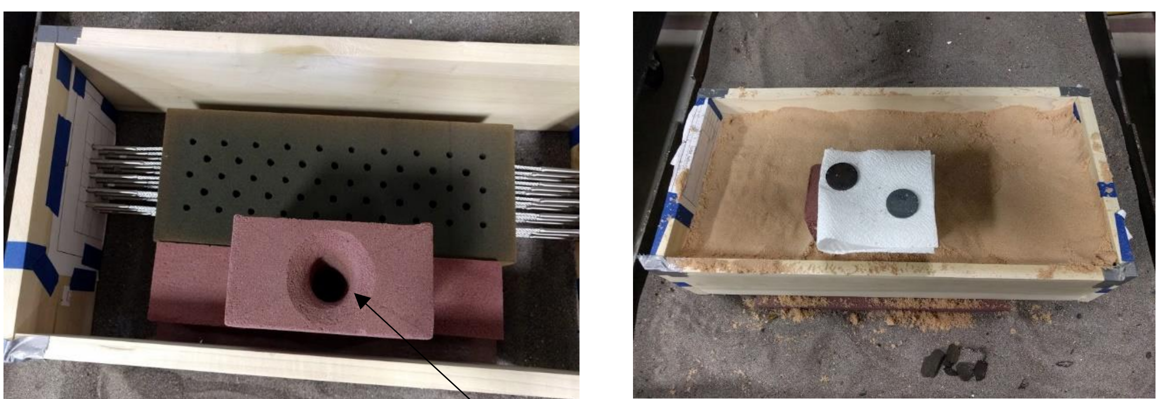
Once the molds were the printed, the next step was to place the fibers in the molds and assemble such that casting can be completed. Here the fibers used are galvanized steel wires, which have 1/8 inch diameter. This was chosen based on the design criteria discussed in Section 2.3. A rectangular wooden frame was built with steel wires held in threaded swage studs before placing inside the molds as shown in Figure 3-9. Each layer of steel wires were placed after every split mold and then tightened. Swage studs were rotated to tighten the steel wires and achieve tension in the fibers. The number of rotations was kept consistent for all the steel wires and the tightening was ensured to engage the steel wires in tension. An outer mold was constructed consisting of downsprue and channel so that metal could fill the 3D printed molds. A channel was made for the metal to flow underneath the mold and fill from the bottom as indicated in Figure 3-9b.



(a) (b) (c)

Figure 3-9. Placement of steel wires

The 3D printed molds were placed on the channel with the steel wires held in the wooden frame. The downsprue was placed next to the 3D printed molds connected to the channel. Finally the mold arrangement was completed by packing sand in the wooden frame to hold this assembly of molds and wires in place as shown in Figure 3-10. The outer mold assembly created in this work around the 3D printed molds can also be designed and printed directly using the Binder Jetting AM process.



a) Downsprue c)

Figure 3-10. Mold Assembly

Along with the cellular structure molds, molds for tensile test specimens were created to evaluate the material properties of the cast metal and use them as reference for the cast cellular parts. The evaluation of these specimens is discussed in Section 3.3.2.1.

3.3.1.4 Metal Casting

After the final mold arrangement, A356 alloy was poured to produce the castings. A356 is a common aluminum alloy (Al-7wt%Si-0.3wt%Mg) [61] with a good combination of mechanical properties and castability. Ingots of A356 were melted using electrical resistance furnace in a SiC crucible. The temperature of metal in furnace was limited to 754.44 °C (1390 °F) through measurement from an immersion thermocouple. TiBor (Al-5wt%Ti-1wt%B) was added in the melt for grain refinement and Al-10wt%Sr for silicon modification about 2 minutes before pouring. The temperature while pouring, although not measured, is expected to be ~10-20 °C lower than the furnace.

Both the castings with and without steel wires obtained after the pour are shown in Figure 3-11. The sand present in between the geometries of the castings were cleaned. All the castings including the tensile test specimens were then subjected to standard T6 heat treatment followed by artificial aging. This was done to provide better strength and ductility in the produced structures. The castings were placed in an air circulating furnace and held at a constant temperature of 540° C for 11-12 hours. This is done to bring all the strengthening elements into a solid solution by spheriodizing the silicon particles. The castings were removed from the furnace at the end of the cycle and quenched in a drum of water at room temperature. Also, during the heat treatment cycle, the uncleaned sand from the castings was released due to the burning of the binder. After this, the castings were aged at 154° C for 5-6 hours to increase the strength of the parts.

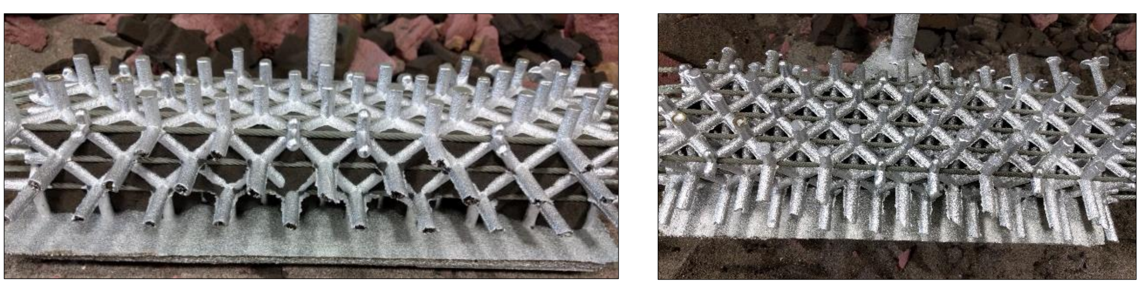


Figure 3-11. Cast parts – Octet cellular structures, before and after sand removal

3.3.1.5 Final Desired Parts

The cast octet-cellular parts were machined using a band saw to attain the final desired shape for further evaluation. Octet cellular structures are shown in Figure 3-12 while Figure 3-13 shows the final machined octet cellular castings with steel wires (fibers). The resultant castings were found to be completely filled and fully homogenous as shown in Figure 3-12 and Figure 3-13. The steel wires were all held in place as designed and the octet cellular structures with fibers were successfully fabricated. The octet structure with steel wires weighed 1.46 kg and the octet structure without wires weighed 1.18 kg.

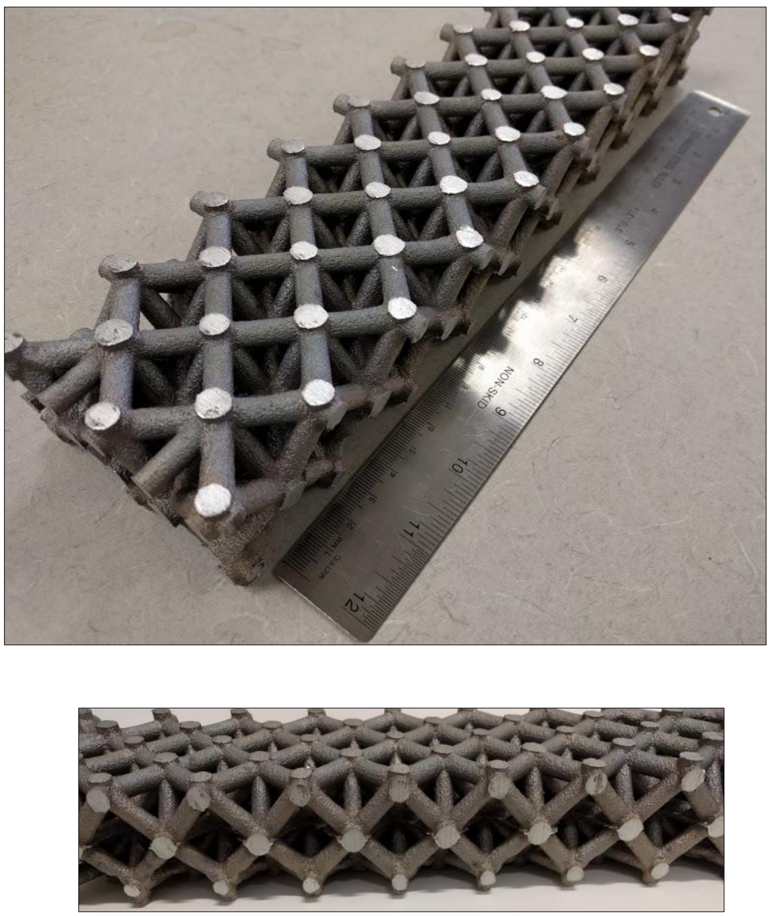


Figure 3-12. Octet cellular structure

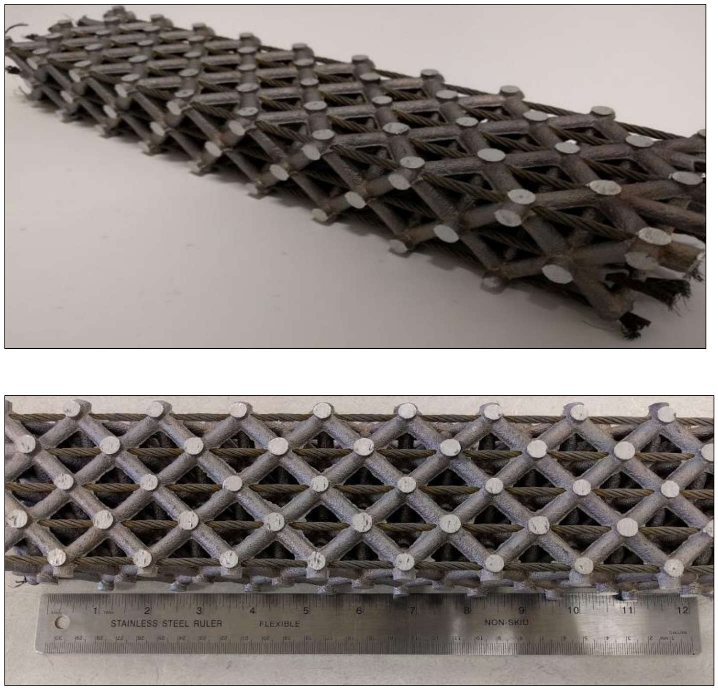


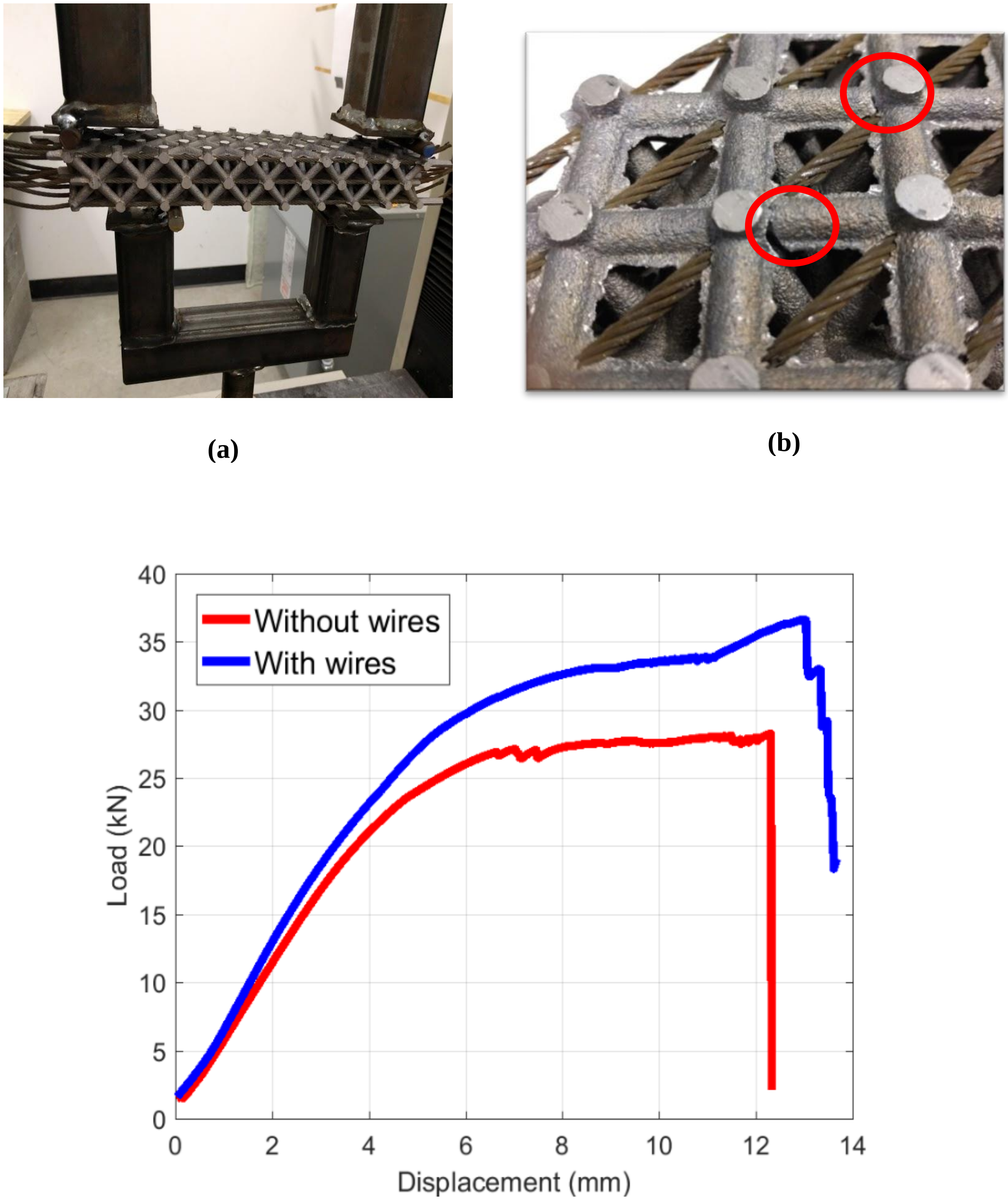
Figure 3-13. Octet cellular structure with steel wires

3.3.2 Experimental Methods

3.3.2.1 4-point Bending Test

4-point bending test was carried out on both the fabricated structures using a custom-built testing fixture. The test was conducted on MTS Insight using the control module provided by MTS. Figure 3-14a shows the structures set on the fixtures for testing. The region between loading points were subjected to constant bending moment and zero shear force. The maximum value of bending moment is to be found in this region. Tests were conducted at constant displacement rate of 2 mm/min to achieve quasi-static loading condition according to the military standards: MIL-STD-401 DIN 53291.

The displacement of loading points and the loading data were acquired during the tests. Figure 3-14c indicates the maximum displacements caused in both the structures during the test for the acquired loads.



(a) (b)

(c)

Figure 3-14. (a) 4-point bending test setup (b) Comparison of load and deflection in octet structures with and without steel wires c) Failure regions

Table 3-1 indicates the failure loads for each of the structure and the corresponding bending stiffness values, which were calculated based on the data from Figure 3-14c.

Table 3-1. Results – 4-point bending test

Structure	Failure load (kN)	Bending Stiffness (N-mm^2)
Octet Structure with fibers	36.59	6.69 x 10^9
Octet Structure without fibers	28.242	5.73 x 10^9

The load needed to cause failure in octet structure with steel wires is observed to be 36.59 kN, which is 8.348 kN more than the failure load for octet structure without wires. The slope of the curves (difference in slope – 1100 kN/mm) in the elastic region, as shown in Figure 3-14b suggest that the bending stiffness of octet structure with steel wires is larger. The displacements caused in the octet structure with steel wires is lower as the load increases. The specific bending stiffness of octet structures with fibers were 5 x 10^{12} mm^3/s^2 and for octet structures without fibers, it was 4.9 x 10^{12} mm^3/s^2. The gain in specific bending stiffness due to the fibers, calculated using the data from Figure 3-14c, was 1x10^{11} mm^3/s^2. The increase in specific bending stiffness is limited by the use of steel wires, which increase the overall weight considerably. However, the overall strength is shown to increase by 30%.

As shown in Figure 3-14b, the failure first occurs in the aluminum strut and the steel wires are still intact. The steel wires are still engaged when the stresses in aluminum are beyond elastic region and this increases the ultimate strength of the structure. The wires are seen to perform more efficiently in the plastic region since they were not pre-stressed initially but only held in enough tension to engage while testing. In the plastic region the wires are at their maximum potential and hence the ultimate strength is observed to have increased more than the stiffness.

3.3.2.2 Characterization Study

The purpose of this study was to characterize the interface between the steel fibers and A356 alloy material. An A356 specimen embedded with steel wire was considered for characterization. The sample was polished using conventional polishing methods. The SEM images are shown in in Figure 3-15a. The embedded fibers can be clearly seen with the metal surrounding them. The interface region between fiber and metal is indicated in Figure 3-15b.

SEM images also indicate the presence of voids in the between the fibers, which means the metal has not infiltrated the fiber region completely. Use of squeeze or vacuum casting could improve the infiltration of metal around the fibers.

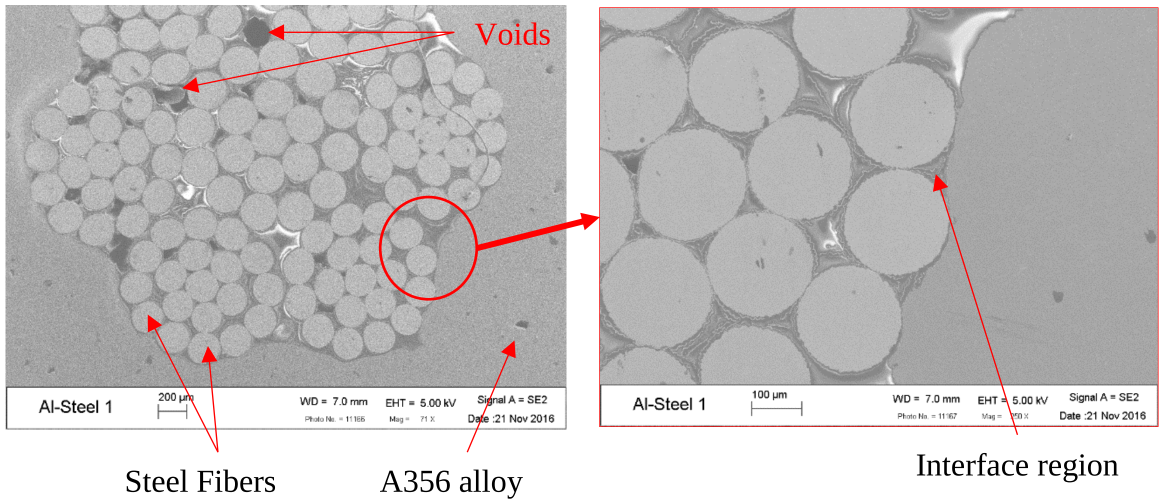


Figure 3-15. SEM images of the cross section

The cross-section was characterized using EDX for fiber, interface and metal regions. The results for the three regions were studied. The regions are indicated in Figure 3-16, where the spectrum studies were conducted.

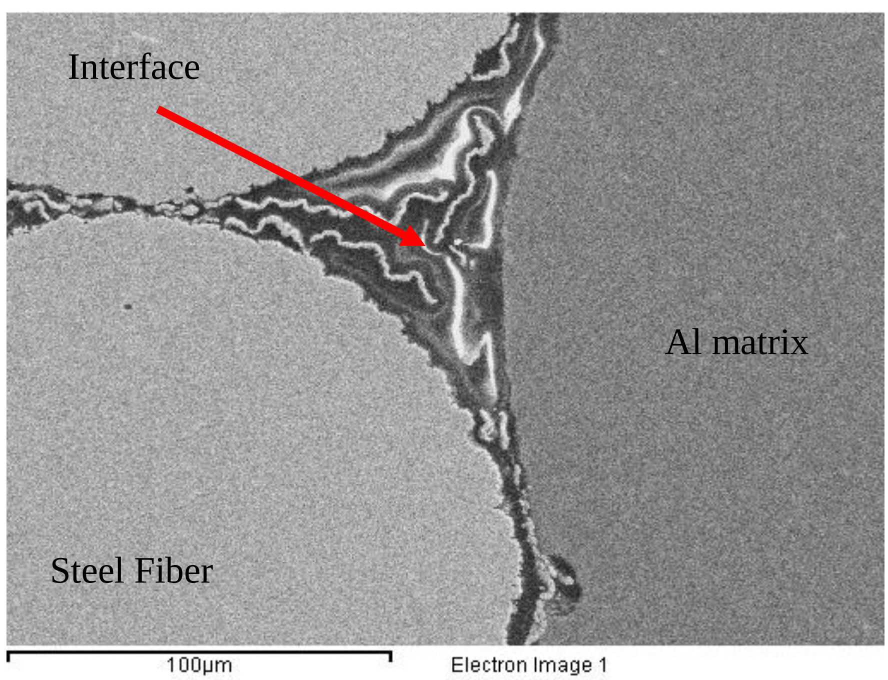
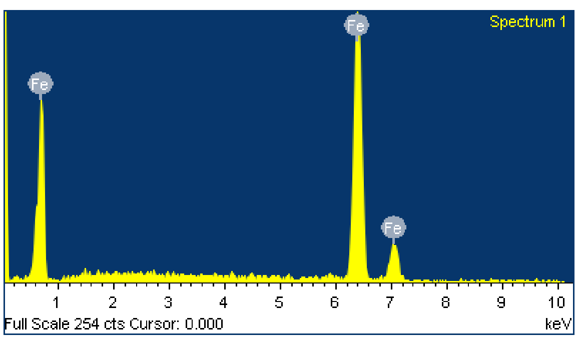
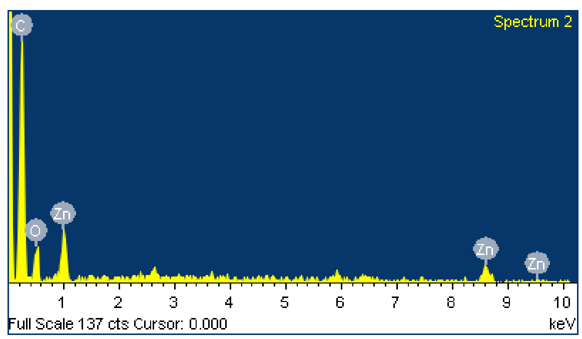


Figure 3-16. Three spectrum areas for EDX study

As shown in Figure 3-17a, fiber region indicated the presence of iron. The interface region between the wire and aluminum was studied and high presence of carbon was found, as shown in Figure 3-17b. This is attributed to the presence of epoxy, which was grinded during the polishing procedure. Also, due to the non-conductivity of the epoxy the area has brightened during SEM study. The Al matrix region indicated the presence of aluminum and silicon (i.e., A356 alloy material), as shown in Figure 3-17c. The high content of silicon is due to the presence of uncleaned colloidal silica solution, which was used in the final step of polishing. The details of the composition of the elements from each spectrum is provided in Table 3-2. In the interface, the presence of the zinc is due the disintegration of the coating on the commercially acquired braided steel wires. However, there was no presence of aluminum or steel to indicate chemical bond. The increase in strength of A356 specimens with steel fibers is, thus, attributed to the presence of a mechanical bonding. The braided steel wires provide a rough surface for the aluminum to lock onto the wire during the casting process.



(a)



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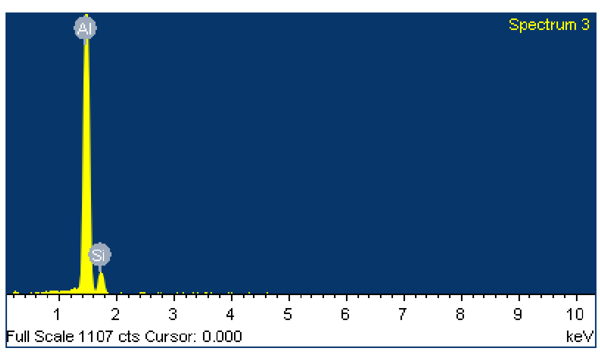


(c)

Figure 3-17. EDX results of three regions (a) spectrum 1 (b) spectrum 2 (c) spectrum 3

Table 3-2. Composition of elements - EDX

Regions	Element Composition	Weight %	Atomic %
Fiber	Fe	100.00	100.00
Interface	C	69.93	80.41
	O	20.30	17.53
	Zn	9.77	2.06
Al matrix	Al	82.50	83.07
	Si	17.50	16.93

3.3.3 Comparison: Modeling and Experimental Results

The models from Chapter 2 were again analyzed and the results were produced using the materials properties calculated from the tensile tests (Appendix B and Appendix C). The braided steel wires were found have an effective modulus of 145 GPa.

Figure 3-18 depicts the differences between the simulation and experimental testing solutions. For octet structure without wires, a strong correlation with an error less than 2 %, is observed. This error can be due to the non-uniformity of struts in the fabricated parts. While the struts were designed to be of diameter 7 mm, the average strut diameter in the fabricated parts was found to be around 7.2 mm, which makes the structures stiffer than the simulation.

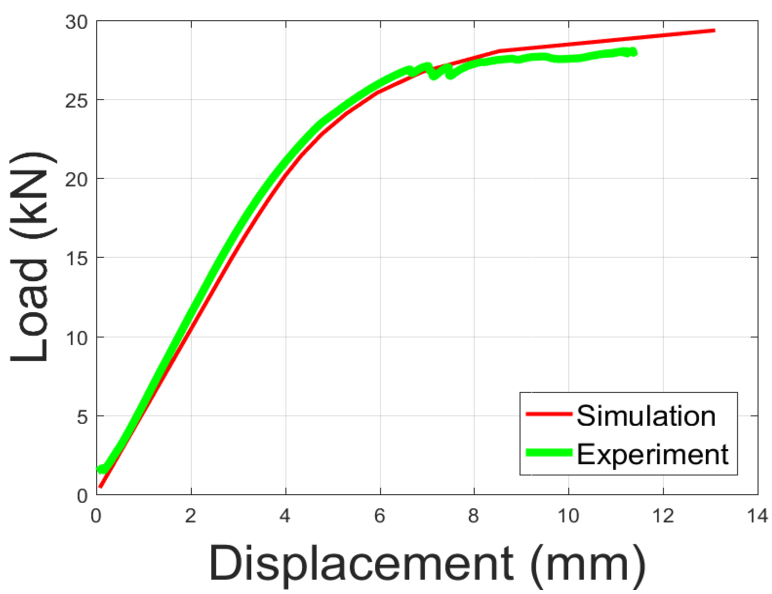


Figure 3-18. Comparison - Octet cellular structure

Figure 3-19 indicates the simulation and experimental solutions for the octet structures with steel wires. For the structure with wires, the error is at the most 2% at lower strains and at higher strains it is 9.44%, which is taken to be within the acceptable range. This discrepancy can be attributed to the bonding issues between the wires and aluminum. The simulation assumes perfect bonding, while in reality this may not be achieved. The properties of fibers were based from non-heat treated steel wires (Appendix C). However, the steel wires in fabricated structures were heat treated. This is also responsible for the error that exists between simulation and experimental results.

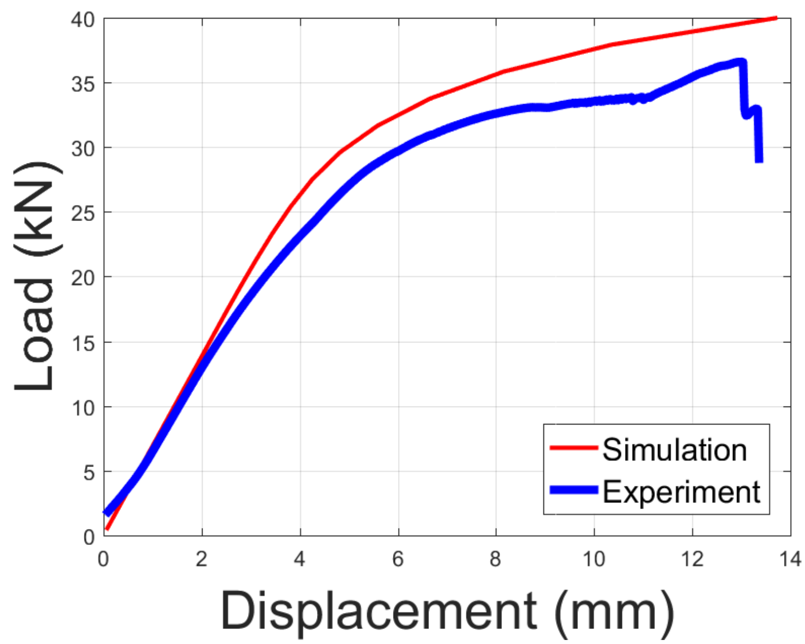


Figure 3-19. Comparison - Octet cellular structure with steel wires

3.3.3.1 Comparison: Set 2

Another set of octet cellular structures with and without fibers were fabricated and tested. The fabrication process followed the exact same procedure as detailed in Section 3.3.1. The overall dimensions, strut and fiber dimensions, and the material remained the same (Section 3.3.1.1). However, for this set the 4-point bending test fixtures were changed, as shown in Figure 3-20. The loading pins moved closer with a gap of 152.4 mm between them. Due to the different fixtures, the response of the structures changed from the previous result (Section 3.3.2.1).

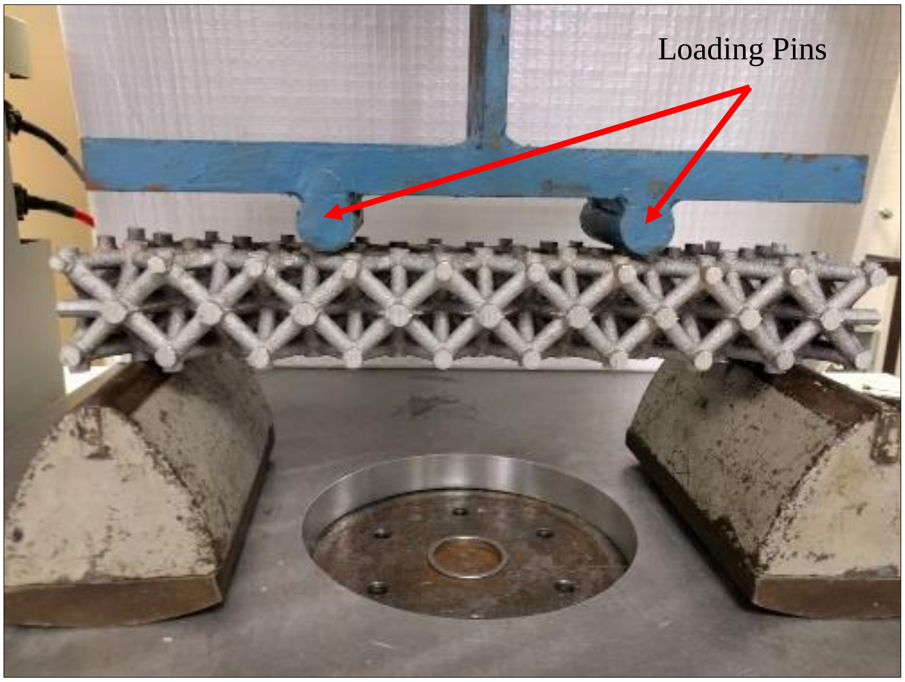


Figure 3-20. Testing fixture: Set 2

The boundary conditions in the analysis was changed to match the testing fixture of second set. For this set, the material properties were assigned based on the first set (Appendix B). Due to the material shortage, the control specimens for the second set were not fabricated. The simulation results were again compared with the experimental tests as shown in Figure 3-21 and Figure **3-22**.

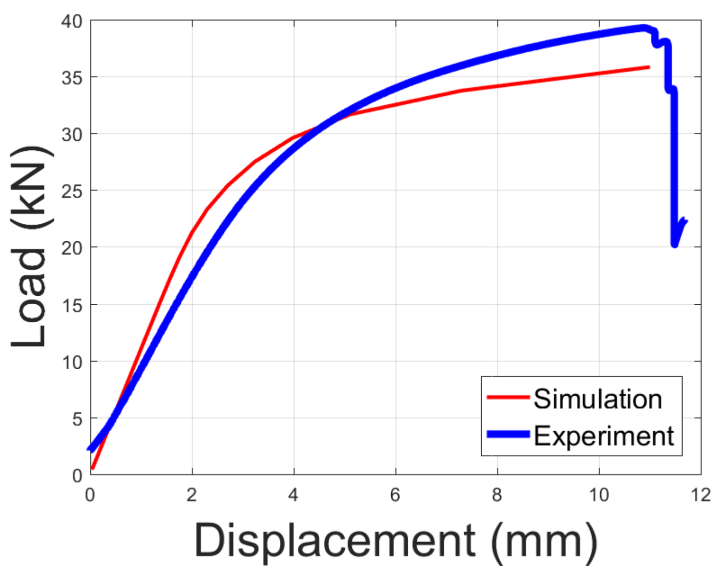


Figure 3-21. Comparison - Set 2: Octet Structures without fibers

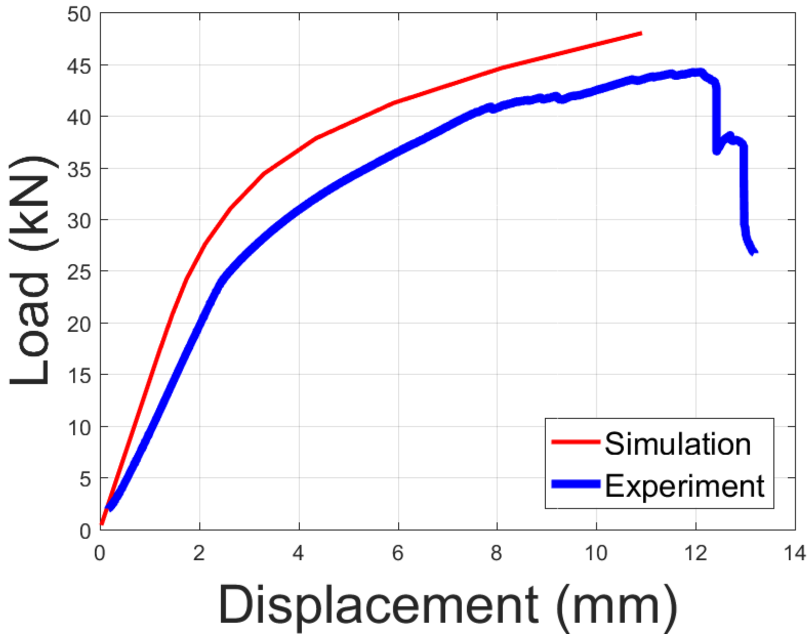


Figure 3-22. Comparison - Set 2: Octet Structures with fibers

Figure 3-21 indicates the simulation and experimental results for octet structures without fibers. At lower strains, the error was found to be 4%, and at higher strains, the error was 8%. Similarly, Figure 3-22 compares the simulation and experimental results for octet structures with fibers. For lower strains, the error was found to be 4%, and for higher strains, the error was 6%.

The discrepancy present in this set of structures is attributed to the same factors as the first set, which are the dimensions of struts, bonding between fibers and cellular material and the use of material properties of non-heat treated steel wires. Additionally, the material properties of A356 alloy were used from the first set, which is also responsible for the error. However, there is still good correlation between the simulation and experimental results, which underlines the predictability of the process.

3.4 Closure

A process to create octet cellular structures with tensegrity behavior was presented combining Binder Jetting and traditional metal casting techniques. Steel wires were chosen as fibers through a study on the strength of A356 tensile test specimens embedded with fibers. The characterization of the interface between steel and A356 revealed the presence of mechanical bonding. Selective embedding of steel fibers was achieved using the split molds printed via Binder Jetting. The process created homogenous octet cellular structures with long continuous fibers.

For an increase in weight of 0.28 kg, the octet structures with steel wires demonstrated higher bending stiffness of 0.9×10^9 N-mm^2 and higher overall strength by failing at 36.59 kN. The specific bending stiffness increased by 1×10^{11} mm^3/s^2. The failure was seen to first occur in the strut material while the steel wires were still intact. This proves that the overall strength is indeed increased by the presence of fibers. The modeling and experimental results of two sets of structures were compared to prove the predictability of the process. The error was found to be as low as 2% for octet structures without fibers and 6% for octet structures with fibers. The interface between the fiber and cellular materials was studied and it was concluded that only mechanical bonding is present. In future, bonding needs to be improved between fibers and cellular metal. Fibers, which have high modulus for low mass need to be processes so that bonding can occur. In this way, the gain in strength can be achieved with very low increase in mass.

4 CONCLUSIONS

4.1 Summary of Research

The goals of this work were:

- Increase the knowledge about incorporating tensegrity behavior in cellular structures and present design guidelines required to realize such structures.
- Develop octet cellular structures with tensegrity behavior using long continuous fibers and improve structural performance in bending applications.
- Devise a process and evaluate the consequent effect of tensegrity behavior in cellular structures by studying the bending performance of the fabricated structures.

Chapter 2 seeks to answer the design focused research questions while Chapter 3 answers the Manufacturing based research question. The summary of methods employed to answer the research questions in each chapters is present in the following sections.

4.1.1 Chapter 2: Design Focused Research Questions

The goal of this work was to enhance the bending performance of cellular structures with tensegrity behavior and due to the lack of a design methodology to achieve this, the following question was framed.

Research Question 1: *What are the design considerations for cellular materials such that tensegrity behavior can be incorporated?*

The arrangement of the structural components in the pomelo and tensegrity structures inspired the design methodology. The fibers in these structures are placed such that they are engaged in tension to enhance energy absorption and overall strength of the structures. Based on the observation of the long continuous fibers present at the nodes in tensegrity arrangements, the following hypothesis was stated.

Hypothesis: *Fibers can be connected between the nodes of octet cell structure so that they undergo tension while octet structure only experiences axial stresses. This can lead to tensegrity behavior devoid of bending stresses.*

The design considerations to develop octet cellular structures with tensegrity behavior were explained based on the process of using AM for embedding long continuous fibers in cellular geometries. The modeling approach used 2D analysis to determine the placement of fibers such that they were engaged in tension to increase strength and stiffness. The fibers were connected at the nodes of the cell structure (Section 2.2.2).

The octet cellular structure, a stretch dominated lattice, was selected as the appropriate cell topology to introduce tensegrity behavior because it experiences only axial stresses. For the octet cellular structure analysis (Section 2.2.4), the arrangement of fibers was similar to the 2D analysis. 3D beam and solid analysis with the loading conditions of 4-point bending test (maximum load 20 kN) were conducted on the octet structures with fibers to evaluate the increase in stiffness and strength. Nearly tensegrity behavior was observed by studying the bending stresses present in the strut (Section 2.2.6).

The integration of tensegrity behavior in cellular structures has not yet been reported. As a consequence of this, there is a lack of understanding about the effects of tensegrity in cellular mechanics and hence, the following research question was prompted.

Research Question 2: *How does the tensegrity behavior affect the mechanics of cellular material?*

The structural elements of tensegrity arrangements undergo either tension or compression and hence, gain a high overall strength devoid of bending. The fibers engage in tension to provide stability and high stiffness to the structures. Based on this observation, the following hypothesis is stated for octet cellular structures when designed with long continuous fibers.

Hypothesis: *The interplay of tensegrity behavior introduced through embedded fibers and mechanics of cellular materials will cause enhanced structural performance under bending applications.*

Once the tensegrity behavior is achieved, the strength and stiffness of the octet cellular structures was studied based on the maximum stresses and displacements occurring in the structures. 4-point bending test loading was conducted for the analysis study and the bending stress was evaluated. The bending stresses were observed to decrease by 66.6% (Table 2-4) in the octet cellular structures with fibers. The fiber engaged in tension to help in decreasing the bending stress. Due to the presence of low bending stress this mechanics is stated as nearly tensegrity behavior. The decrease in maximum stresses and displacements as reported in Table 2-2 and Table 2-3 proved that the effectiveness of fibers.

The octet structures with fibers showed improved performance under bending loads with a decrease in maximum stress of 75 MPa and maximum displacement of 2.2 mm.

The analysis was expanded to establish a design criteria to make design decisions while developing a cellular structures with long continuous fibers. The corresponding parametric study showed the variation of maximum stress occurring in the structures for different sizes of struts and fiber while the material properties were fixed.

4.1.2 Chapter 3: Manufacturing Focused Research Question

Development Question: *How to fabricate large metal cellular structures with continuous fibers?*

There is a need to develop a controlled reliable manufacturing process to realize cellular structures with tensegrity behavior. For this, a major requirement is the selective placement of fibers.

Development Hypothesis: *Using Binder Jetting AM and metal casting, long continuous fibers can be selectively placed in sand molds to produce cast cellular structures with tensegrity behavior.*

In the context of development, in Chapter 3, a novel manufacturing process combining Binder Jetting and Metal Casting was developed to solve the manufacturing challenges and realize tensegrity behavior. Also, this process addresses the limitations of traditional manufacturing techniques and direct metal AM processes. Long continuous steel (braided) fibers were selectively placed in novel octet cellular structures with tensegrity behavior. The fibers were selectively located in the complex sand molds printed using Binder Jetting and metal was cast to achieve fully homogeneous octet cellular structures with tensegrity behavior.

In addition to the modeling solutions, it was necessary to realize and evaluate the octet cellular structures with tensegrity behavior. The goal of this work was to evaluate the performance of fabricated structures under 4-point bending tests and compare the overall strength. Due to the lack of a controlled manufacturing process, the performance and failure mechanisms of tensegrity structures is not clearly understood. The cellular structures with tensegrity behavior have neither been fabricated nor evaluated under any loading application. There is a need to understand the performance quantitatively and measure the effects due to the presence of long continuous fibers. Therefore, this work was guided to gain a basic understanding of the structures and the following research question was framed.

Research Question 1: *What is the bending performance of cast metal cellular structures with tensegrity behavior, introduced using long continuous fibers?*

The fiber arrangement in tensegrity behavior decreases the deflection of the overall structure and engage in tension to reduce the stresses present in the struts. This was applied to the current understanding of cellular structures to present the following hypothesis.

Hypothesis: *Using Binder Jetting AM and metal casting cellular structures with tensegrity behavior can be produced using long continuous fibers. This controlled process is shown to produce reliable structures. The cellular structures with fibers can then be evaluated using 4 point bending tests and compared to the structures without fibers. The presence of tensegrity behavior is expected to improve the bending performance of the cellular structures.*

The fabricated structures were subjected to 4-point bending tests and the overall strength of the octet structures with fibers was 36.59 kN, which was 8.34 kN higher than the overall strength of octet structures without fibers (Section 3.3.2.1). The interface between the fiber and octet cell material was found to have only mechanical bonding through the EDX study conducted for the cross-section (Section 3.3.2.2). Also, the modeling solutions matched experimental results with an error of less than 6 % for lower strains and 9.6 % for higher strains (Section 3.3.3), showing the predictability of the process chain devised to fabricate octet-cellular structures with tensegrity behavior.

4.2 Limitations and Future Work

While developing the octet cellular structures with tensegrity behavior, in this research study, limitations were encountered. These limitations and the potential areas of improvement are discussed in the following subsections, which are divided based on the chapters reported in this work.

4.2.1 Chapter 2: Design of Fiber-Reinforced Cellular Structures with Tensegrity Behavior

The design of cellular structures with long continuous fibers assumed that the fibers were perfectly bonded with the cellular material. This was not achieved, in reality (Section 3.3.2.2), and for future work, models should accommodate sliding between fibers and cellular structures. This will help in elimination of errors while matching experimental results with modeling solutions.

The work presented here aimed to gather attention to a new design method; however, this approach can be improved to achieve better results. The placement of fibers in cellular geometry was based on observations in a 2D analysis. By using topology optimization schemes and different placement strategies can be explored through which better results can be expected.

New Research Question 1: *How to leverage topology optimization to identify placement of fibers in a cellular structure model for enhanced structural performance?*

The pre-tensioning of fibers affects the overall strength and stiffness of structures. This research study ensured pre-tensioning by tightening the fibers to engage in tension when loaded. However, there is a need to include these effects and therefore, determine the level of pre-tensioning necessary for the fibers so that better structural characteristics are achieved. The pre-tensioning can make the structure stiffer but it would also cause the cellular structure to undergo compressive loads. The effects of pre-tensioning can be applied to benefit the structure under certain load conditions, for example when deflection is not desired.

New Research Question 2: *How does pre-tensioning of fibers affect the cellular structure mechanics?*

4.2.2 Chapter 3: Fabrication and Testing of Cellular Structures with Tensegrity Behavior

The fabrication approach involved assembling the 3D printed molds and then packing with additional sand with a channel and a downsprue to achieve final mold assembly. This additional work of assembling can be avoided by designing the channel and downsprue in the digital mold design and directly produced via Binder Jetting.

In this research, braided steel wires were used as fibers, which increased the weight of the overall structure by 20%. This was done to present a proof of concept. Although the overall strength increased by 30%, the total weight increase was 15%. There is a need to study and process high strength fibers to bond with metal alloys. The same increase in strength can be achieved with even less weight-increase if fibers such as carbon-fiber, silicon-carbide and alumina are used since their stiffness to mass ratio is considerably higher than steel wire. Additional metals can be used for cellular materials but compatibility between the fiber and metal needs to establish.

New Research Question 3: *How to pre-process high strength fibers to establish interface bonding between the fibers and metals for Binder Jetting and metal casting process?*

The properties of braided steel wires were acquired from tensile testing of wires, which were not heat treated. In future, the steel wires need to undergo heat treatment before their properties are evaluated so that the error between the simulation and experimental results can be decreased.

Also, there is need for a controlled tightening process of fibers. The consistency of pre-tensioning needs to be maintained to ensure all the fibers engage at the same time. This improvement in process can reduce the error between modeling and experimental results. During the 4-point bending test of the octet structures, the strains occurring in the struts need to be studied to evaluate the bending stresses occurring in reality. This further evaluation study will increase the knowledge about the effects of tensegrity behavior on cellular structure mechanics.

In addition to the new research questions, the following discussion provides the future work that can benefited from this study.

- Topology optimization can be implemented to decide the placement of fibers in cellular geometries and tailor the stiffness and strength based on the loading. The deformations of models under loading can be used to optimize the placement of fibers to minimize the deflection and stress present in the structures.
- Multifunctional cellular materials can be created using cellular structures with fibers. A hierarchical arrangement of cellular architecture with continuous long fibers can be used for different types of loading (static, impact, thermal, etc.). Also, vascular

fibers can be used to achieve multi-functionality in these structures. The design arrangement can be based on the functionality requirements and the constraints that are present.

- From a material science perspective, a study on pre-processing of fibers can be conducted to establish a bonding between the fiber and metal being cast. Improved bonding between the materials will ensure better structural properties and predictability.
- Other casting techniques such as squeeze casting and vacuum casting can be introduced to ensure complete filling and also, aid in bonding between fibers and metal. However, these techniques are accompanied with complicated tooling and are only viable for lower melting point alloys (zinc, copper, aluminum, etc.).

4.3 Publications

The format of this dissertation includes planned publications as chapters.

Table 4-1 lists the chapters as publication titles with the publication plan.

Table 4-1. Publication Plan

Chapter	Submission Status	Journal
Design of fiber-reinforced cellular structures with tensegrity behavior	Planned - 2016	Acta Materialia
Fabrication of cellular structures with tensegrity behavior using 3D printed sand molds	Planned - 2016	Advanced Functional Materials

4.4 Research Contributions

In accomplishing this work, design steps were established to create octet cellular structures with tensegrity behavior using long continuous fibers. By introducing tensegrity behavior in cellular materials, a new type of mechanics was achieved. The designed structures were fabricated using a novel manufacturing process combining Binder Jetting and metal casting, and evaluated for bending performance through 4-point bending tests. The following contributions are:

- Design steps to introduce tensegrity behavior in cellular structures using long continuous fibers (2.2).
- An understanding of effects of tensegrity behavior on structural performance of cellular materials (Section 2.2.4 and Section 2.2.6).
- An understanding of the performance of the octet cellular structures with tensegrity behavior under bending application (Section 3.3.2.1).
- A manufacturing process to selectively place and embed fibers in cellular geometries to enhance structural performance (Section 3.3.1).

APPENDIX A - FIBER-MATERIAL SELECTION

In chapter 2, the designs of cellular structures with tensegrity behavior using long continuous fibers were modeled and analyzed. In analyzing the structure the assumption was that there is perfect bonding between the fiber and cellular structure at the node. This condition needs to be satisfied before creating such structures. If there is no bonding then the fibers will fail to engage in tension when the load is applied and hence there will be enhanced bending performance. The fiber material has to be well bonded with the cellular structure in order to produce tensegrity behavior. Therefore, there is a need to understand the compatibility between the materials before they are embedded in structures.

In this study A356 aluminum alloy is used as the material for cellular structure. So to choose the fiber material, a compatibility study was conducted. The following fibers were acquired in long continuous tows and the bonding between them and A356 was studied through evaluation of cast tensile test specimens.

- *Unsized carbon fibers:* Carbon fibers without coatings were placed in A356 tensile test specimens. The acquired fibers had a high modulus of 296 GPa [62], which makes them suitable for embedding in octet structures. Previous studies using squeeze casting have shown that these fibers increased overall strength and flexural modulus of aluminum composites [63] by 60%. The formation of interface and its effects has also been studied [64]. Hence, these fibers were selected for the compatibility study.
- *Nickel coated carbon fibers:* 3 variants - (Ni - 22.5%, 32.5% & 55%) of nickel coated carbon fibers were embedded in the A356 tensile test specimens. These fibers, which were acquired, had a modulus of 206 GPa [65] , which is suitable for this research. Previously, nickel coated carbon fibers were used in aluminum matrix as reinforcements, where increased (80%) wear resistance was measured [66]. Also, the effects of interface with variation of Ni on the mechanical properties of final aluminum composite has been reported [67].
- *Nextel 610:* Nextel 610 are alumina fibers with a high modulus of 380 GPa. The varying strengths of aluminum matrix with alumina fibers were studied and an increase in flexural strength of the composites was reported [68]. Aluminum

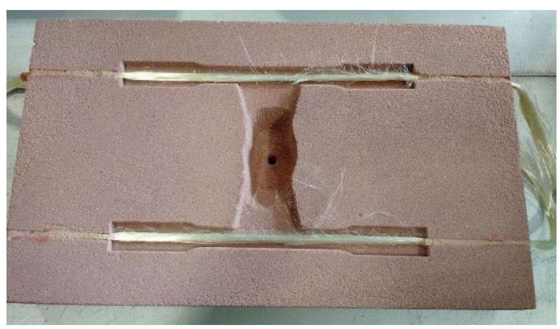
composite wire with Nextel 610 fibers was reported to have a mean strength of 1380 MPa and was developed using an infiltration method [69]. This made a good case for Nextel 610 to be tested for this research work.

- *Steel wires:* The interfacial reaction between steel and aluminum has been studied [70]. A process for making steel-reinforced aluminum members has been reported [71]. Braided steel wires, with modulus of 145 GPa, were specifically chosen due to the imperfect surface that can get locked with aluminum.

Casting process

Tensile test specimen patterns with dimensions 8 inch x 0.5 inch x 0.2 inch were created. These patterns were used to create molds and fibers were placed in the middle of the patterns as shown in Figure A-1. Narrow channel was made along the length of tensile pattern was made in the mold and fibers were held in place by packing sand in the channel.

a)



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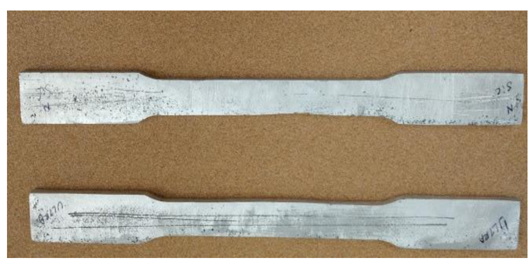

d)

Figure A-1. Tensile test specimens a) patterns b) fibers c) mold d) cast and machined part

A runner and downsprue were created to for the cast metal to flow and fill the mold. A356 aluminum alloy was poured into the mold to produce the castings. Similar casting process was used as described in Section 3.3.1.3. The castings were cleaned and machined to get the tensile specimens as shown in Figure A-1d. Tensile test specimens without fiber material were also cast for evaluation and comparison.

Experimental Testing

The goal of this testing was to evaluate the bonding strength between the fibers and A356 alloy. The tensile test specimens with the fibers were cast and the machined parts were subjected to tensile testing. The tensile test results were compared to the performance of specimens without fibers to evaluate the bonding between the fiber and A356 alloy material.

Two variants of Ni-coated carbon fibers (32.5% and 55%), Nextel 610 fiber and unsized carbon fiber specimens were not involved in the testing process since the fibers freely moved during manual inspection of the castings. The fiber length, which extended out of the specimen, was manually stretched and the fibers pulled out without any effort, indicating that there was no presence of bonding between the fibers and A356. Specimens including nickel coated carbon fibers (22.5%) and steel wires were tested for their tensile performance and the results are shown in Figure A-2.

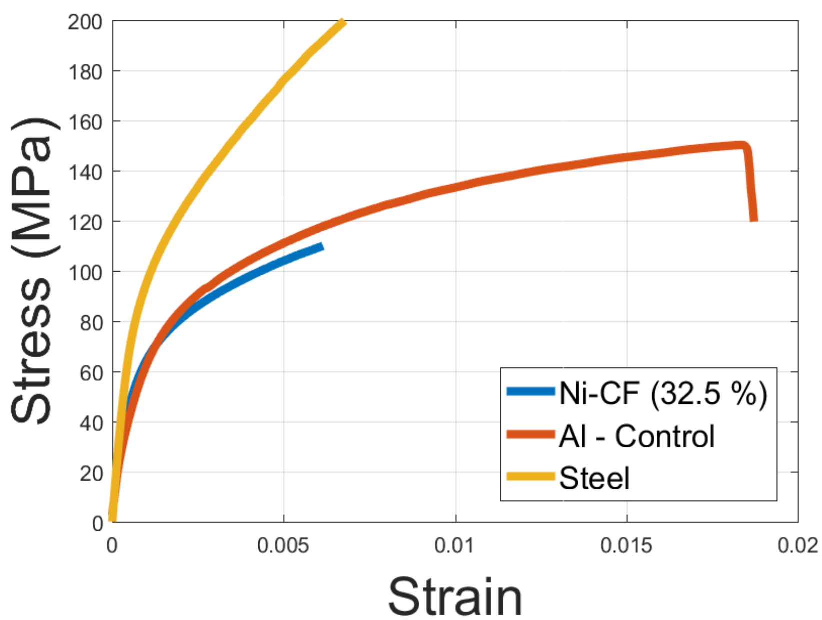

Figure A-2. Tensile test results – fibers

Nickel coated carbon fibers (N-CF) did not show much improvement in these tests; rather their performance was inferior compared to the pure aluminum specimen. After testing, the fractured specimens were again subjected to manual inspection and the fibers (Ni coated CF and SiC) pulled out of the specimen easily. There was no metallurgical bond holding the fiber in A356 alloy material.

Studying the tensile test results of specimens with steel wires, it clearly indicates an increase in the stiffness and overall strength. The steel specimen failed at 200 MPa while aluminum failed at 140 MPa. The steel wires increase the stiffness by 20% at lower strains. The wires were still held strongly inside the material when the fracture specimens were manual inspected. It is important for the fiber to bond with cellular structure like in the case of steel and A356 so that structural performance can be enhanced. Hence, in this study, steel wires were used in the octet-cellular structures and integrated in the molds before casting.

APPENDIX B - TENSILE TESTING OF A356 SPECIMENS

Two tensile test specimens were also cast during the production of octet-cellular structures. Tensile testing was conducted on these specimens to evaluate the material properties of A356 cast for that trial. The young's modulus of the material was found to be 71 GPa, which was calculated by averaging the values from both the tests. The test results are shown in Figure B-1 and the modulus from both the curves was found to be differing by 1.5 GPa. These results were used in the modeling of octet cellular structures.

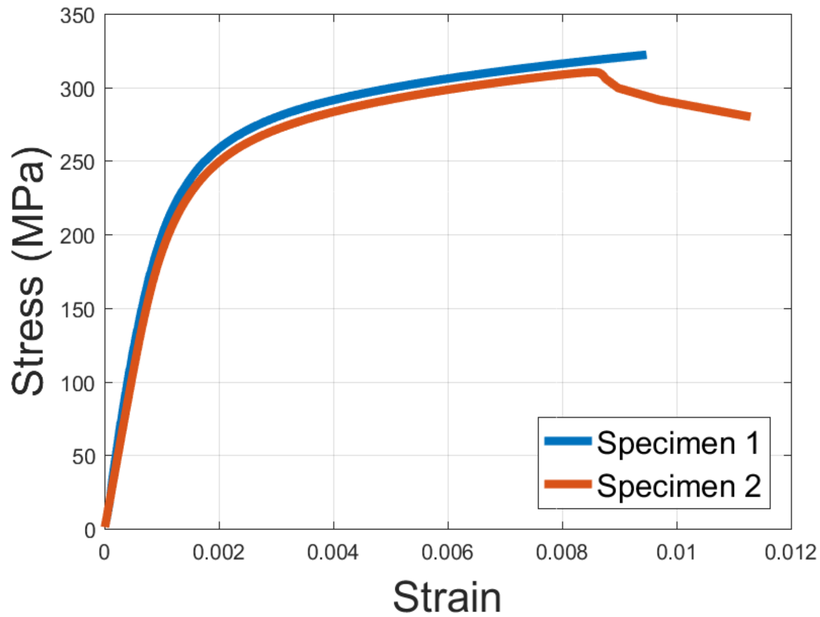

Figure B-1. Tensile test - control specimens

APPENDIX C - TENSILE TESTING OF BRAIDED STEEL WIRES

Two specimens of braided steel wires were subjected to tensile test with a guage length of 46.3 mm to calculate the effective modulus**.** Figure C-1 indicates the results from the test. The effective modulus is given by the following relation:

$$\boldsymbol{E} = \frac{\boldsymbol{W} * \boldsymbol{L}}{\boldsymbol{S} * \boldsymbol{A}} \qquad \text{Eq. C-1}$$

Where, E is the effective strand modulus (GPa), W is the applied load (kN), A is the cross sectional area of the wire and S is the elastic stretch. Based on the results in Figure C-1 the effective modulus value E was calculated for the two specimens and the average value was about 145 GPa, with a standard deviation of 10 GPa. It is important to note that, these wires were not heat treated unlike the ones present in the fabricated structures (Section 3.3.1.5).

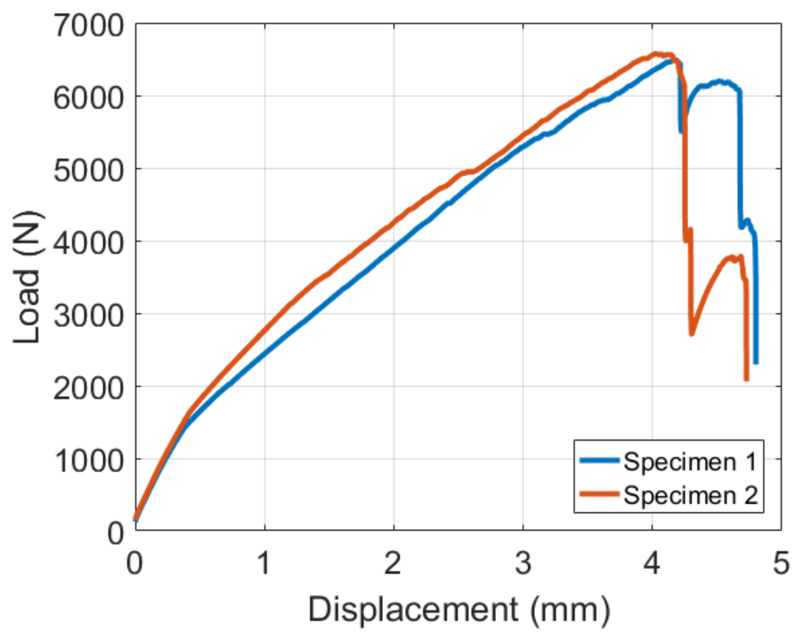

Figure C-1. Tensile test results - braided steel wires

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