Experimental Investigation of Flexural Properties of Fibre Glass Reinforced Polymer

Author

Asad Abbas

MS (Design and Manufacturing Engineering)

Reg. No. 274441

Supervisor

Dr. Muhammad Salman Khan

Department of Design and Manufacturing Engineering

School of Mechanical and Manufacturing Engineering (SMME)

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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Abstract

Additive manufacturing is an advanced manufacturing technology in which computer aided design is converted into STL file and then fed to 3D printer after slicing the design with the help of slicer software. Masked Stereo-lithographic apparatus (MSLA) is a type of liquid based 3d printer in which an array of LED is used to cure the photosensitive polymer resin with the help of ultra violet radiations. These radiations solidify the resin on platform of printer when fall on exposed area. The platform rises for next layer and this process continues until all the layers are cured and part is manufactured. The time to manufacture the part depends on layer thickness, height of part and the orientation of the part on platform. These parameters are set during the slicing process. We can find many applications of SLA printers in fields like engineering, medical, dentistry, jewelry and many others. These printers now a day are used to manufacture the final parts apart from the prototypes but there is limitation in the availability of resin of required mechanical strength. So to overcome this problem researches are carried out to manufacture polymer composites in different ways. This research focuses on using short glass fibres of different strand lengths as reinforcing material to matrix photosensitive polymer. The glass fibres of 5, 10, 15, 20, 25, 30, 35 and 40 mm lengths are used as reinforcing materials and nine specimens including neat one are manufactured in MSLA printer. The flexural properties of these specimens are obtained by performing 3-point bend test on universal testing machine as per ISO 14125 standard. The graphs of the force vs deflection are obtained and flexural strengths and flexural modulus is calculated and compared for all the specimens. It was observed that the flexural strength as well as flexural modulus of these specimens was increased initially for 5 and 10mm strands lengths and then started decreasing as the strands length increases. The maximum value of flexural strength and flexural modulus was obtained for 10mm glass fibre length and minimum for 40mm.

Key Words: *Additive manufacturing, Flexural properties, Discontinuous fibres, Glass fibres, SLA printer, Stereolithography.*

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CHAPTER 1

INTRODUCTION

When choosing a production strategy for a particular product, several different considerations must be taken into account. The following are crucial variables that influence the choice of manufacturing: cost, quality, surface finish, internal defects ease of manufacturing and geometry of the part to be manufactured.

To manufacture a part with less cost, short time and with high accuracy always remained a field of interest for researchers. A lot of manufacturing techniques are used to fabricate the part are being used in different fields as per requirement and most advanced are additive manufacturing. This research focuses on the additive manufacturing technique to manufacture a part with high strength. This is done by using one of the techniques of additive manufacturing known as stereolithography by reinforcing short glass fibres in the resin to enhance its mechanical properties. In this chapter we will discuss some basic introduction about the additive manufacturing, its types and we will focus on the Stereolithogrphy as it is our topic of interest.

1.1 Additive Manufacturing

Additive Manufacturing is also known as 3D printing is a technique of manufacturing a part in layer-by-layer process in 3D printers by adding the required material unlike subtractive manufacturing in which part is manufactured by removing the extra material through different processes like turning, drilling, boring, milling and grinding (Watson and Taminger, 2018). In additive manufacturing a part is designed in CAD/CAM software and is converted into Stereolithogrphy (STL) file and then sliced using some slicer software. The model is then fed to the printer for manufacturing (Figure 1). Due to its numerous benefits like design flexibility, rapid prototyping, print on demand, strong and light weight parts, fast design and production, minimizing waste, cost effective and environment friendly etc. manufacturing is used widely in different field of research and industries (Mehrpouya *et al*., 2021).

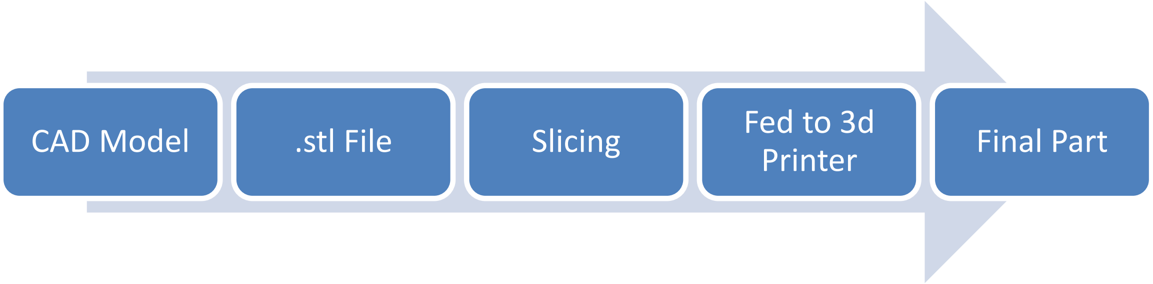


Figure 2 Additive manufacturing process flow diagram

There are multiple applications of additive manufacturing in wide variety of fields such as design and manufacturing, health care, dentistry, rapid prototyping, industries, sports, engineering more commonly automobile and aerospace.

Apart from several advantages, additive manufacturing also has some disadvantages which limit its usage for some applications these include limited raw material, restricted build size of 3D printers, post processing of build part, skilled person for manufacturing etc. (Mohanavel *et al*., 2021). Additive manufacturing process uses a range of materials from polymers to metals and ceramics depending on the application of the part being manufactured. The additive manufacturing is further divided into three types depending on the base material used in the printer. These are solid based, powdered and liquid based.

Due to the paradigm shift it has brought about in the way things are produced, additive manufacturing (AM), often known as 3D printing, has been dubbed the third industrial revolution. Traditionally, it takes several steps to go from a raw material to a fully finished, assembled, and useable product. By adopting this procedure, functional items can be generated directly from the raw material at a fraction of the time previously consumed. As a result, AM has found use in a number of industries, including printed electronics, aircraft, automotive, and healthcare. Given its ability to accurately and precisely create patient-specific customized implants, additive manufacturing (AM) is being employed more frequently in the healthcare industry. Some applications of AM technologies include rib cages, bones, and implantable heart valves manufacturing. Using 3D printing, a wide range of materials, including ceramics, metals, polymers, and composites, have been processed to create complex implants. Dental implants for the maxilla, dentures, and various prosthetic devices are among the dental applications of AM. It can also be utilized in surgical planning and training since AM makes it simple to generate anatomical models. (Bhargav et al., 2018).

1.2 Types of Additive Manufacturing

An element or segment of a designed feedstock material is added as part of an additive manufacturing (AM) process to create a part. These materials can include ceramic, metal, and polymeric and plastic materials. A certain method can be used depending on the needs. Different processes make use of various deposition methods. Some of them transform the materials into semisolid form, while others melt the materials. Material states can be altered using a variety of heating sources, including lasers and resistive heaters.

Rapid manufacture, solid freeform fabrication, direct digital manufacturing, layered manufacturing, and 3D printing are only a few of the many names given to AM in the literature (Santos et al., 2006). AM can be further divided into several methods such as fused deposition modeling (FDM), selective laser sintering (SLS), stereo-lithography (SLA), electron beam melting (EBM), and binder jetting depending on the state of the printed matter, i.e. liquid, solid, or powder (Figure 2). Plastics, metals, ceramics, and composites are just a few of the materials that can be utilized in additive manufacturing, depending on the technique. However, the supply of materials that are suitable for use in additive manufacturing is still somewhat restricted. In order to fill this gap, researchers are attempting to introduce novel materials and materials prepared/processed to achieve the aforementioned characteristics. As in many situations, specific special characteristics are required, such as mechanical strength, electrical conductivity, thermal endurance, durability, and multi-functionality (Ribeiro et al., 2020).

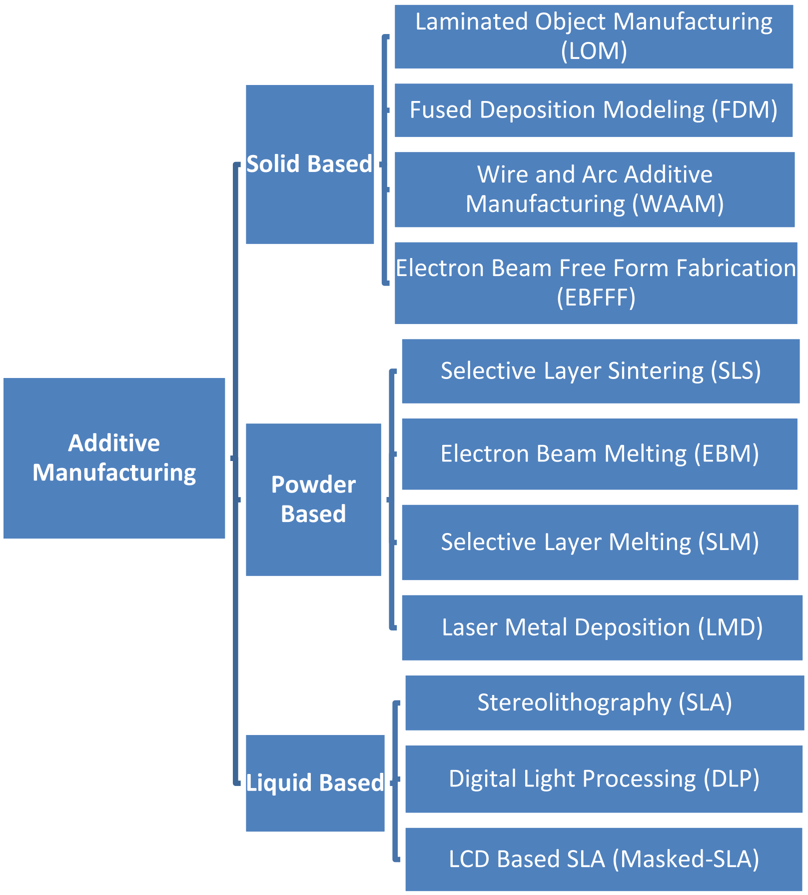


Figure 3 Types of additive manufacturing based on the state of printed material

1.3 Stereolithography

The most popular form of AM is stereolithography (SLA). SLA prints the required 3D shape by using a powerful laser to cure liquid resin in a reservoir. Using a specialized format, the SLA "slices" solid 3D CAD data into two-dimensional cross sections for laser photo curing (STL file). The form created by the sliced data is drawn onto the liquid resin by an ultraviolet (UV) laser beam that focuses on the surface of a bath of photo curable resin. The resin hardens wherever light is present, forming a solid layer of sliced data from CAD design. The process is carried out layer by layer until the three-dimensional object is printed. Stereolithography equipment generally comes in three types: laser SLA, digital light processing (DLP), and masked SLA (MSLA). Masked stereolithography (MSLA) is the most effective and trustworthy of these. With the use of an LED light source that is directed by an LCD projector, SLA resin is cured in Masked. In comparison to other SLA techniques, MSLA has exceptionally high levels of precision and surface polish. The feedstock are in liquid form during this process, and after coming into contact with a light ray (laser, UV, etc.), they solidify and create each layer. This procedure is known as the SLA's curing stage. The thickness of each layer cannot exceed a predetermined value depending on the characteristics of the feedstock material and the intensity of the light emitted as the materials solidify through light curing. Additionally, the reflectivity of materials is crucial to the fabrication process (Jacobs, 1995). After a layer has formed, the ram of the sample holder drops, following the general idea of all AM processes, and a new layer is successively deposited and solidified. To have a strong 3D component, nevertheless, there might be some adjustments and considerations depending on how complicated the geometry is. The terms supports, overhangs, and undercuts are used to describe these features (Kruth et al., 1998).

SLA printers are further divided into three types based on the curing source. These include laser-based SLA, DLP based SLA and Masked SLA printers (Kafle *et al*., 2021). Due to the highlighted significances of SLA printers, they hold diverse applications in multiple domains such as medicine and dentistry, education, automotive, printed electronics, engineering, aerospace etc. (Bhargav *et al*., 2018). In medicine SLA manufacturing is applied to design scaffolds for the purpose of tissue engineering, ex-vivo tissues production and regenerative medicine are of significantly important in present time (Singh and Ramakrishna, 2017). The prosthetic aids, dentures and maxillofacial implants are the recent applications of SLA printing in dentistry (Bhargav *et al*., 2018). SLA printers are also used in automobile industry to manufacture tools and in some cases finished part ranges from interior part to dashboard etc. With advantages of lightweight and strength of composite parts manufactured by SLA, we can find its applications in aerospace such as manufacturing of door handles, dashboards etc. (Koronis *et al*., 2013).

SLA prints the required 3D shape by using a powerful laser to cure liquid resin in a reservoir. Using a specialized format, the SLA "slices" solid 3D CAD data into two-dimensional cross sections for laser photo curing (STL file). The form created by the sliced data is drawn onto the liquid resin by an ultraviolet (UV) laser beam that focuses on the surface of a bath of photocurable resin. The resin hardens wherever light is present, forming a solid layer of sliced data from CAD design.

1.3.1 Applications of SLA

In terms of the freedom of design for the structures that are to be constructed and the scales at which these can be built, stereolithography is a reliable freeform fabrication process. It has a promising future for biological applications, particularly when used in conjunction with MRI and CT scans. It has been demonstrated to facilitate, expedite, and enhance surgical operations such implant placements and difficult surgeries. Stereolithography has also been used to create custom biomedical products, such as hearing aids, and implants with anatomically correct shapes. The creation of novel polymers has made it possible to directly construct implantable gadgets like biodegradable scaffolds for tissue engineering. Hydroxyapatite composites, peptide-grafted structures, cell-containing hydrogels, and modified natural polymers have all been developed. Stereolithography has evolved into a broadly applicable method for biomedical engineering with the advent of hydroxyapatite composites, peptide-grafted structures, cell-containing hydrogels, and modified natural polymers (Melchels et al., 2010).

In the medical field, several writers started with the medical records of a particular patient to build a notion for a personalized intervertebral fixing device (Moldovan et al., 2018). Additionally, special medical equipment can be created to help the surgeons do some difficult surgeries. SLA technologies are used in industry to create 3D models of parts for better understanding and inspection, master models for future moulds (example: jewelry sector), supports or cases for various circuits and sensors, ornamental pieces, and drones (Doicin et al., 2016)

The creation of sophisticated, cell seeded 3D structures like synthetic scaffolds is crucial to the advancements made in reconstructive medicine, where tissue engineering plays a significant role. Applications of 3D fabrication techniques in biomedical research have exploded since the late 1980s. Applying a suitable 3D synthetic scaffold while cells nest for their proliferation and refabricating of loose tissue is one of the most promising strategies in tissue repair (Dhariwala et al., 2004; He et al., 2011). It is well known that the performance of the scaffold is impacted by the many properties of created 3D structures. The average pore size, porosity ratio, average pore size distribution, and interconnectivity between cavities are significant factors in the cell/scaffold structures. Surface topography and the mechanical behavior of the synthetic scaffolds are other traits of interest (Kim et al., 2011).

The SLA is a 3D printing process that has received FDA (Food and Drug Administration) approval. The first FDA-approved 3D-printed medicinal agent was offered as Spritam (levetiracetam) tablet for epileptic seizures treatment. Additionally, because to the 3D design, additional biological 3D printing technologies like SLA raise hopes for new generations of treatments and regulated reagent release rates. The SLA-fabricated drug administration platform with drug loading may also be an appropriate aperture for therapeutic agent injection in the target tissue (Kempin et al., 2017).

Normal bone healing occurs after birth, however for defects larger than 6 mm, the biological rebuilding mechanism cannot function properly without the use of graft implants or biomaterial replacement (Kebede et al., 2018). SLA bone scaffolds can be used in the innovative, hard-tissue regeneration procedures of tissue engineering. In most cases, a rebuilding approach is used to restore bone abnormalities caused by events like accidents, acute bone tumours that cause loose bone, and chronic diseases. A wide variety of repaired tissue qualities must be met in SLA (Kim et al., 2010).

1.3.2 Manufacturing of Composite through SLA Printer

Manufacturing items with isotropic material characteristics is a desirable feature of vat photo polymerization over material extrusion procedures like fusion deposition modeling (FDM). In the printing plane, FDM parts have the characteristics of the material; however, perpendicular to that plane, the mechanical properties of the part are dependent on the mechanical adhesion of the polymer layers to one another. Vat photo polymerization can be used to create components with mechanical qualities that are almost isotropic (Stansbury and Idacavage 2016). The thermoset polymer is not fully cured within each layer of the part even though it is produced layer by layer, similar to

FDM, before the part is elevated and the following layer is printed. This enables previously unreacted polymer functional groups to interact with the polymer curing in the layer that is currently being printed. Vat photopolymerization can yield components with nearly isotropic characteristics, hence the orientation of the part during printing is determined by how best to optimize the printing process rather than how force will be applied to the completed part (Simpson et al., 2022).

The material qualities of the resins used to make parts are one of the limitations of vat photopolymerization. These resins can only be used for a limited number of end-use structural applications since the pieces they generate are frequently fragile and weak (Ogale and Renault 1991). Incorporating a reinforcement material when making a composite is one way to enhance a material's qualities. Injection and compression moulding have historically been used to create short-fibre composites. The composites can be made using the same manufacturing process as polymers, but with improved material qualities by reinforcing them with short fibres (Agarwal and Broutman 1990).

1.4 Research Gap

Low cost, quasi-isotropic properties and ease of manufacturing are some advantages of short fiber-reinforced parts which make them dominant over continuous fibers to be used for automotive and industrial applications (Capela et al., 2017). From literature review we can find that manufacturing of polymer composite with short glass fiber reinforcement on SLA 3D Printer is not addressed. Effect of fiber length on the flexural strength of composite manufactured through SLA printer was not investigated in literature.

1.5 Research Objectives

- To manufacture the part by glass fibers reinforcement with different fiber lengths on SLA 3D printer.
- To investigate the flexural properties of the specimen.
- To compare the results of reinforced and unreinforced specimens.

1.6 Scope of Research Work

This research will address the process of manufacturing of polymer composite with glass fibres reinforcement. The specimens will be manufactured through Stereolithogrphy 3D printing technique. Reinforcement of fibers will be carried out by manual hand laying method. After the manufacturing of specimens reinforced with glass fibres of different lengths, they will be tested by 3 point bend test on universal testing machine. The results will be compared and conclusion will be drawn.

1.7 Thesis Layout

The book is divided into five chapters. First chapter gives the introduction about the additive manufacturing processes used these days to manufacture the complex geometries. Different types of manufacturing processes and it will focus on stereolithography technique of manufacturing.

Second chapter covers the literature of different researchers who worked on enhancing the mechanical properties of parts manufactured through different additive manufacturing processes by fibres reinforcement.

Third chapter focuses on methodology applied to manufacture the desired specimens with reinforcement of fibres of different lengths and experimentation performed on them to evaluate their flexural properties.

Chapter fourth will cover the results obtained from the experimentation and discussion of these results and chapter fifth will give the conclusion of the research work and future recommendation to improve the flexural properties of the part manufactured through SLA 3D printer.

CHAPTER 2

LITERATURE REVIEW

Various researches have been carried out to study the properties of parts manufactured through different additive manufacturing techniques and to improve their mechanical properties. Cheah et al., 1999 presented the method to improve the physical strength of part manufactured through SLA printer. They added 1.6 mm fibres in 20% wt. and after performing the tests he found an increase in the properties of part (Cheah et al., 1999). Park and his coworkers investigated the flexural strength of parts manufactured through SLA and FDM and compared the both. He found that the flexural properties of parts manufactured through SLA showed significant flexural strength as compared to FDM (Park et al., 2020). Lingesh *et al*, 2014 studied the effect of short fibres of glass reinforcement in blended polymers manufactured through barbender twin extruder. They reinforced fibres in different weight percentages like 5, 10,15,20,25 and 40.

Tensile strength, flexural strength and impact strength were studied. They found that as the weight of fibres increase these properties also increases and got maximum mechanical strength at 25% wt. of fibres. It was observed that mechanical properties of composites increase with the addition of glass fibres (Lingesh *et al.*, 2014). Sano *et al*. studied the technology to fabricate the fibres reinforced composite using continuous and short fibres using SLA printer. They used glass powder and glass fibres for short fibres reinforcement and glass fibre fabric for continuous fibre reinforcement. The findings of the research were that the properties of the powdered and continuous fibres were increased but short fibres had no effect on properties due to non-uniform fibres distribution and presence of voids (Sano *et al.,* 2018). According to another study, carbon fibres were reinforced into polymers to investigate the tensile and fracture strength using SLA printer. While comparing both the properties, results depicted that the tensile strength increased by 5.7% whereas fracture strength rose by 26%. Although an increase in the properties was observed but the research gap is that as carbon fibres were opaque to UV light so it hindered the curing of resin. Glass fibres instead of carbon fibres can diminish the opacity to UV radiations (Parandoush and Lin., 2017). Garoushi et al, 2007 studied the effect of short fibres length on the mechanical properties of short fibres reinforced composites. They prepared the specimens with different lengths from 1 mm to 6 mm and determined the flexural strength of specimens. Three-point bend test was performed on the specimens on universal testing machine. Maximum flexural strength was exhibited by 5 mm part (Garoushi et al., 2007).

The objectives of the present study are to enhance the flexural properties of the material manufactured through SLA printer and to improve the fibres reinforcement method. The investigation and comparison of flexural properties was carried out by 3-point bend test using a universal testing machine (Korkees et al., 2020).

CHAPTER 3

RESEARCH METHODOLOGY

In order to find the flexural properties of fibre reinforced polymer composite the specimen of 80x10x4 mm size was prepared by following the standard given by International Standard Organization ISO 14125 (flexural properties testing for various polymer matrix composites) (STANDARD and ISO, 1998) (Korkees et al., 2020). The Figure 1 gives a comprehensive lookup of the methodology of the current research.

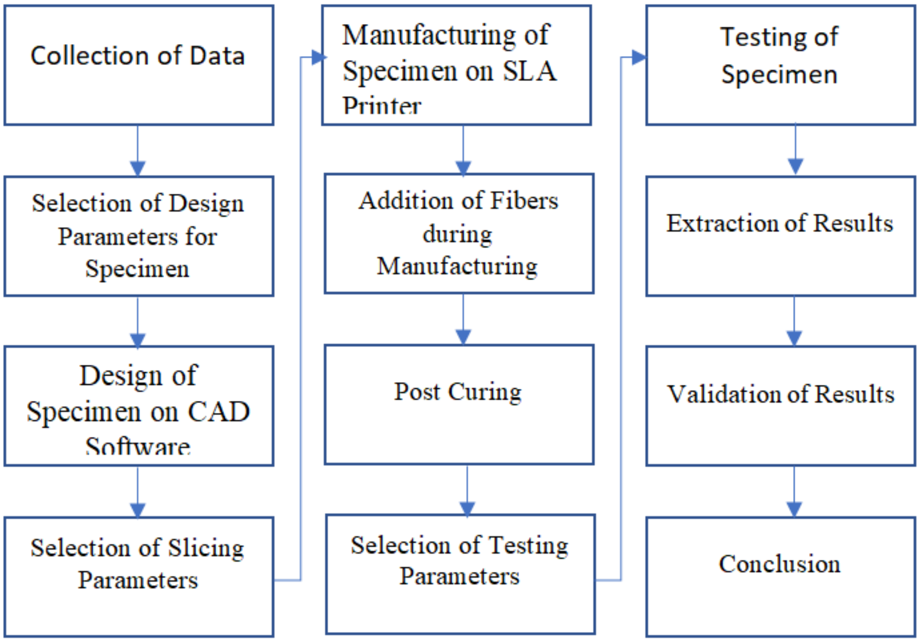


Figure 3 Methodology flow chart

The Specimen was designed by using PTC Creo CAD software which is specifically used for product designing. The File prepared on CAD software was converted into Stereolithography STL file. The converted STL file was sliced using slicing software i.e., Photon Workshop. The 3D printer used to manufacture the part was Liquid Crystal Display (LCD) type Stereolithographic Apparatus (SLA) (Mehrpouya et al., 2021). The printer is manufactured by Anycubic Technology Co. as shown in Figure 4(a) and the glass fibres were obtained from Pakistan Fibre Glass Company Karachi Pakistan Figure 4(b).

(a) *(b)*

Figure 4 (a) Masked SLA 3d printer (b) Chopped glass fibers

For the manufacturing of the part, slicer software was set in order to get the optimum result. Total hundred layers were formed. The height of each layer was set about 0.03 mm. The exposure time for each layer was 8 sec except the four bottom layers which was 40 sec as shown in Table 1 (Piedra et al., 2021). In order to prepare the glass fibre reinforced specimen glass fibres were chopped into different strand lengths i.e., 5, 10, 15, 20 and 40 mm (Figure 3 (b)). The reinforcement was carried out by manual hand laying method. As the sliced part was divided into 100 layers, the reinforcement was performed after every 20th layer. After completion of the manufacturing process, the post curing was carried out by washing the part with ethanol. The manufactured parts are shown is Figure 5. The 3-point bend test was performed on Universal Testing Machine at speed of 1 mm/min and support span length of 60 mm for determining the fracture strength of the part and the results were compared (Yinet et al., 2019) as shown in Figure 6 and Table 2.

Specimens were manufactured with different fibre lengths to investigate their flexural strengths of the specimens.

Table 1 Process Parameters for MSLA 3D Printer

Parameter	Value
Layer Height	0.03 mm
Orientation	0°
Bottom Layer Count	4
Bottom Exposure Time	40
Normal Layer Exposure Time	8

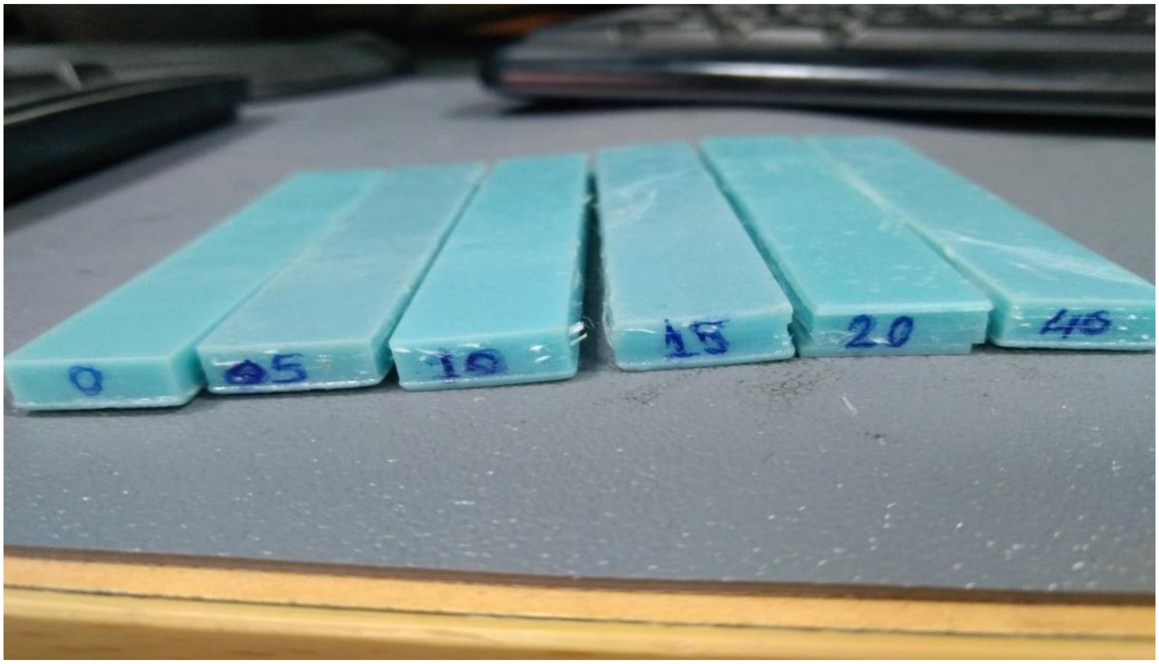


Figure 5 Specimens after manufacturing

The bar was rested on the two supports of the universal testing machine. The force was applied to the specimen and the graph of deflection against load was recorded by 3-point bend test. Figure 7 shows the parts after fracture. Entire composite specimens showed a linear elastic behavior until yield point. The flexural strength was calculated from the simple beam theory for rectangular cross-section as per ISO 14125:

$$\sigma_f = \frac{3FL}{2bd^2}$$ Eq. 1

Where:

σ_f = flexural strength = stress at the outer surface at mid-span, MPa [psi],

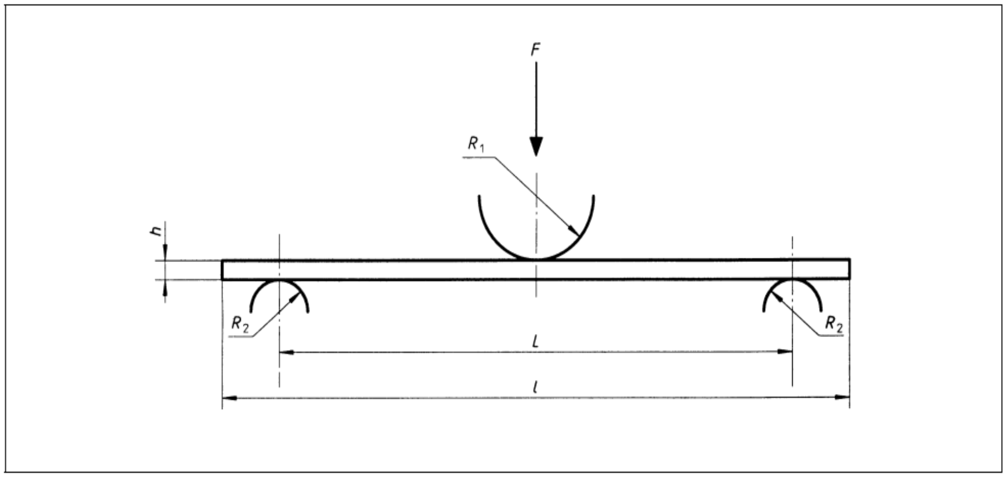
F= applied force, N [lbf],

L= support span, mm [in.],

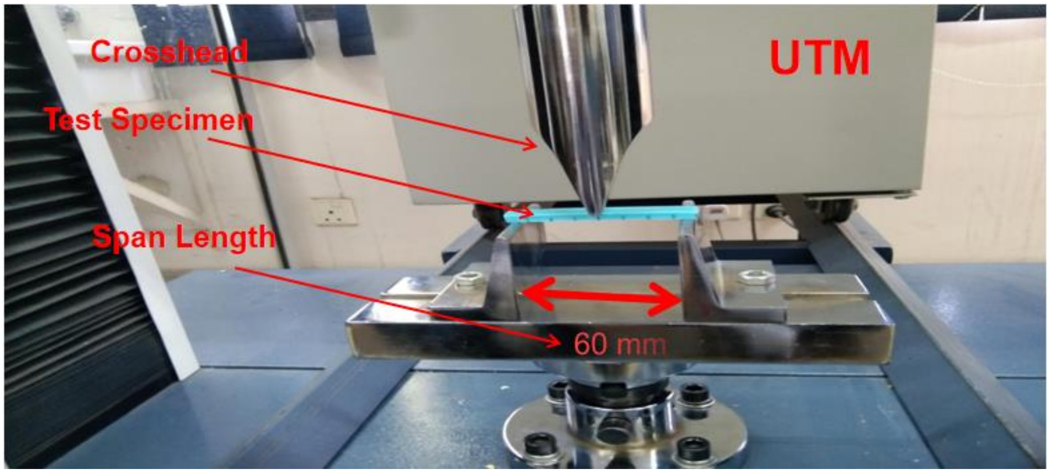
b= width of beam, mm [in.],

d= thickness of beam, mm [in.],

The graph of Flexural Strength against fibre length is shown in Figure 5.



(a)

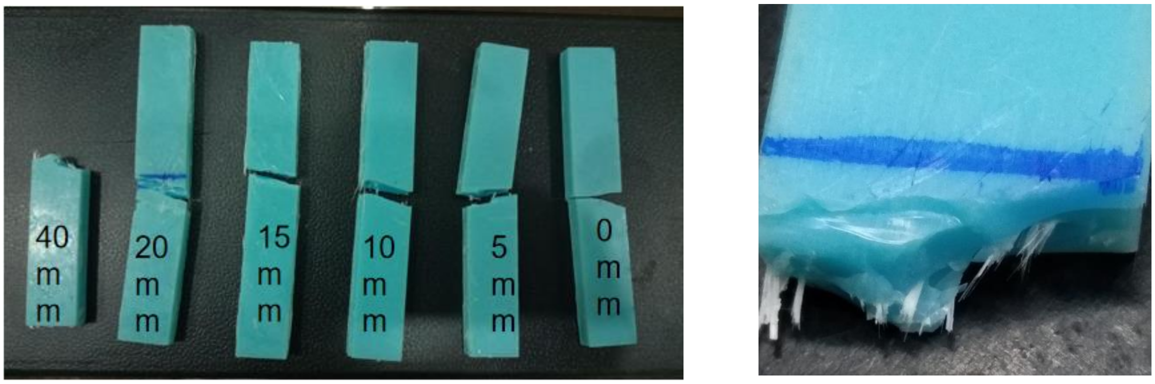


(b)

Figure 6 (a) Three point bend test arrangements as per ISO 14125 (b) Placement of Test Specimen in UTM for three-point bend test

Table 2 Testing parameters

Length of Specimen (l)	80
Length of Span (L)	64
Crosshead Speed (mm/min)	1 mm/min



(a) (b)

Figure 7 (a) Specimens after 3 point bend test (b) Cross-sectional view of specimen after test

The results are compared for all the specimens and the graph of flexural strain against fibres length is shown in figure 5.

$$\varepsilon = 6Dd/L^2 \qquad \text{Eq. 2}$$

Where ε is the maximum strain in the outer fibres and D is the deflection. The flexural modulus *E*b is shown in figure 6 against fibre length and is calculated as

$$E_{\mathrm{b}} = L^3 m/4bd^3 \qquad \text{Eq. 3}$$

Where m is the slope of the tangent to the initial straight-line portion of the load–deflection curve.

CHAPTER 4

RESULTS AND DISCUSSION

In present study the reinforced glass fibres of different strand lengths were used to enhance the flexural properties of the end use products. Although, work on carbon (CF) and kevlar fibres (KF) is found in literature but glass fibres are mostly preferred because the other fibres such as carbon fibres are opaque and they do not let the UV light to pass through them (Parandoush and Lin., 2017). Fibres can be used for reinforcement in two different ways i.e., continuous and short fibre reinforcement however, this research focused on discontinuous fibres (Li et al., 2022). Low cost, quasi-isotropic properties and ease of manufacturing are some advantages of short fibre-reinforced parts which make them dominant over continuous fibres to be used for automotive and industrial applications (Capela et al., 2017). Discontinuous fibres can be used in the three AM techniques which are Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Stereolithography (SLA) (Li et al., 2022). After the three point bend different graphs were obtained against the various fibre lengths.

The four different properties are presented in present research i.e., deflection due to crosshead, flexural strength, flexural strain and flexural modulus. The figure 1 is depicting the deflection due to crosshead before fracture. It can be seen that with increase in the fibre length from up to 10 mm an increase in deflection was observed which means, its load bearing capacity was enhanced. Further increase in the fibre length caused decline in deflection of the specimens. The results of three-point bend test are given in the table 1. Figure 8 shows the result of applied load of unreinforced polymer and graph between load and the deflection can be observed. Similarly the graph obtained for 5 mm fibre length against load is shown in the Figure 9. As the fibre length increases from 5 mm to 10 mm the deflection is also observed to be increased and value of applied load also increases as shown in Figure 10. Similarly the graphs were obtained against other fibre lengths like 15 mm, 20 mm and 40 mm as shown in Figure 11, 12 and 13.

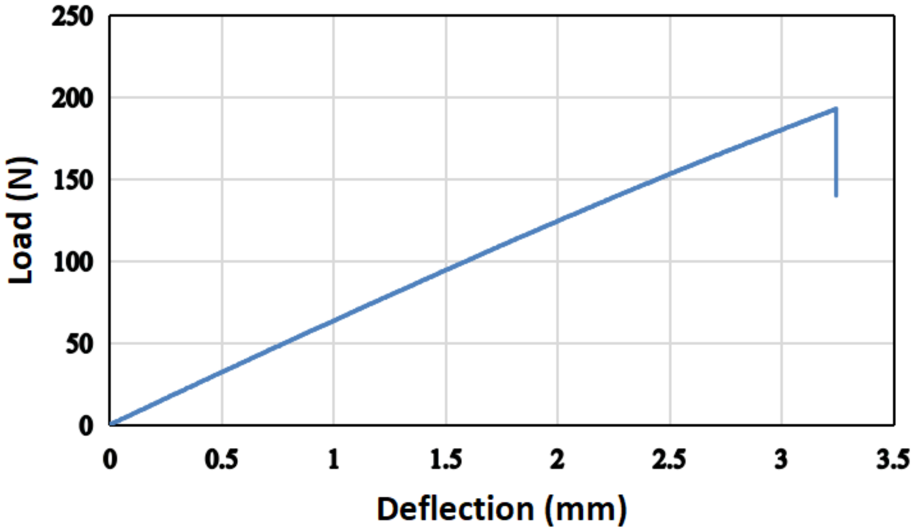


Figure 8 graph of deflection against load of unreinforced polymer

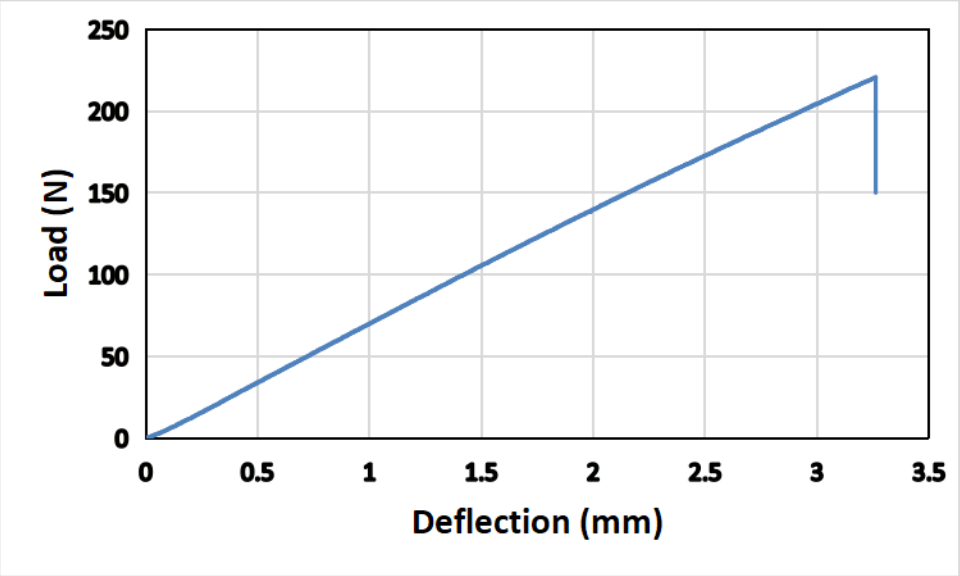


Figure 9 Graph of deflection against load of 5 mm fibre reinforced polymer

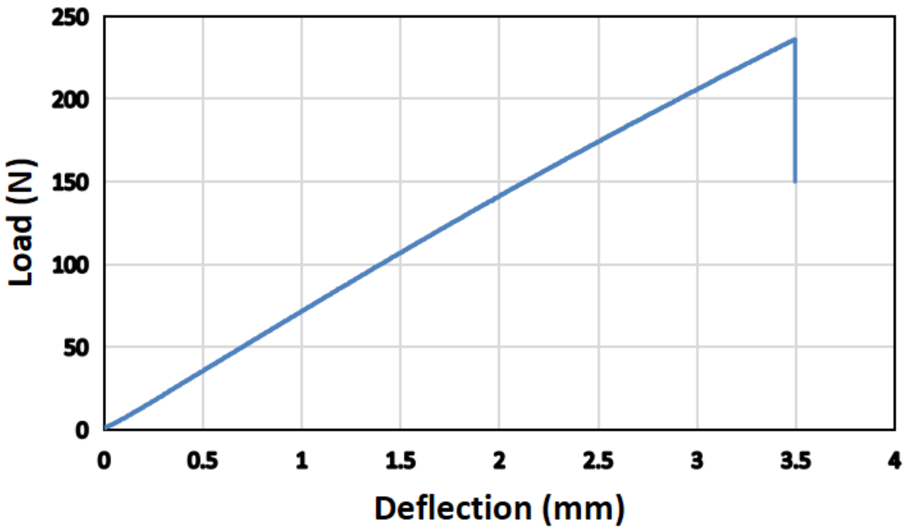


Figure 10 Graph of deflection against load of 10 mm fibre reinforced polymer

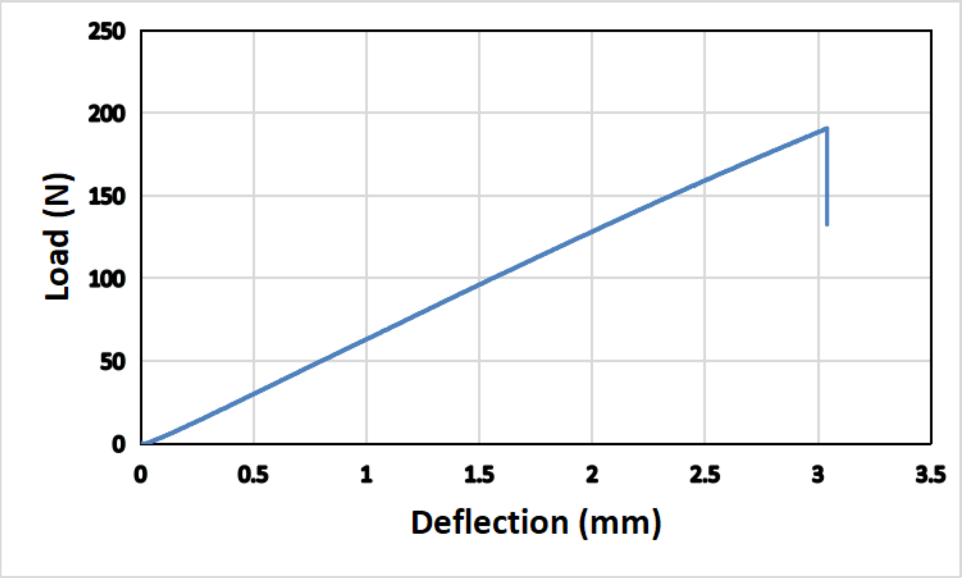


Figure 11 Graph of deflection against load of 15 mm fibre reinforced polymer

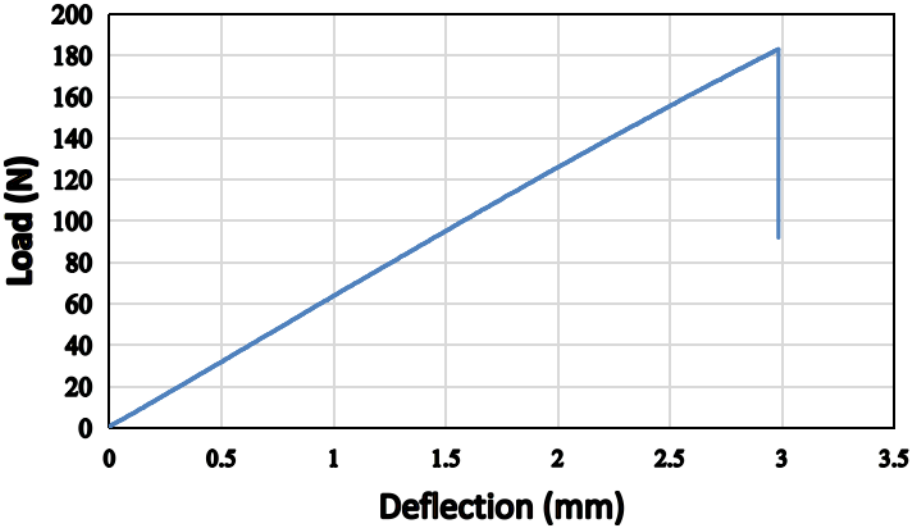


Figure 12 Graph of deflection against load of 20 mm fibre reinforced polymer

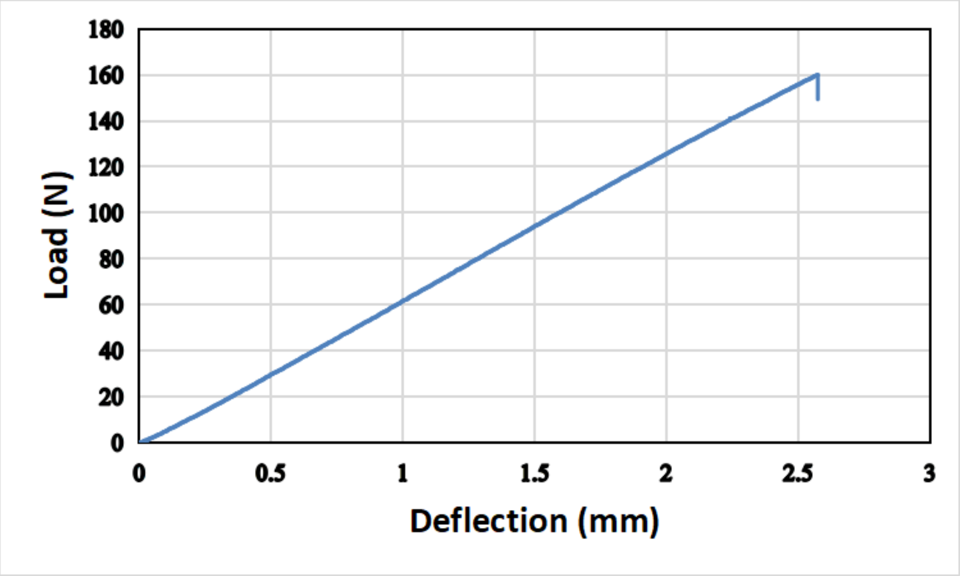


Figure 13 Graph of deflection against load of 40 mm fibre reinforced polymer

Table 2 Deflection and load bearing capacity at various fibre lengths

Glass Fibre Strand Length (mm)	Load (N)	Deflection (mm)
0	192	3.24
5	220	3.55
10	236	3.69
15	190	3.03
20	180	2.98
40	160	2.57

The results of deflections against all the fibre lengths are compiled as shown in Table 2. And for the better understanding of the comparison of deflections and load applied for all the fibres lengths graph is shown below in Figure 14.

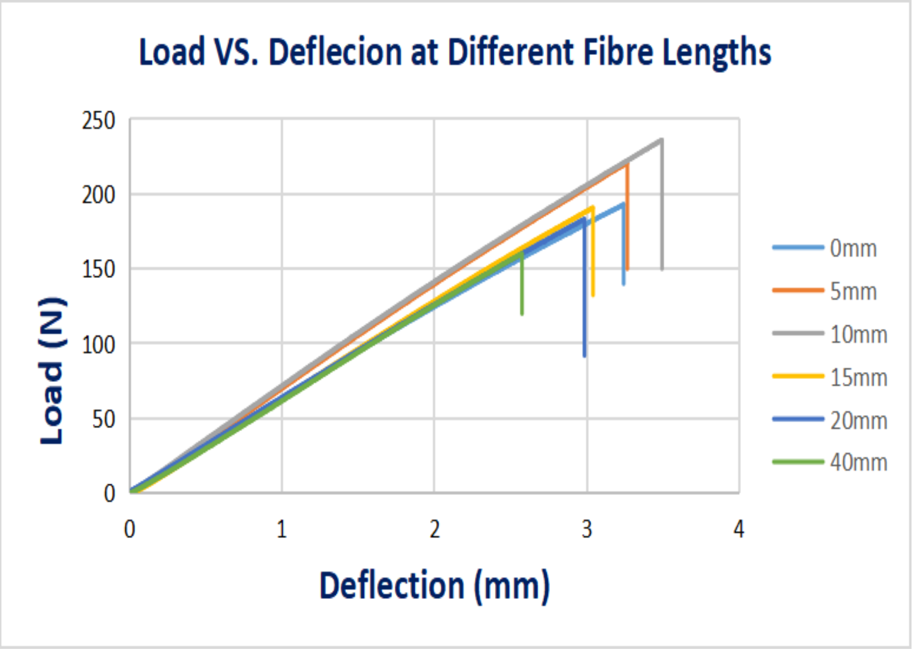


Figure 14 Graph of load vs deflection of specimens at all fibres lengths

In the present research four different properties were studied that are deflection due to crosshead, flexural strength, flexural strain and flexural modulus and the results were compared. Figure 15 is depicting deflection against six different fibre lengths when the load was applied. The unreinforced specimen gave deflection of 3.24 mm and reinforced specimens showed an escalation when fibres length was increased from 5 mm to 10 mm to a value of 3.49 mm. Fu et al. 1999 presented in his research that the flexural modulus increases as length of fibres is increased (Fu et al., 1999). A subsequent decline in deflection was observed when the fibres length was increased beyond 10 mm up to 40 mm.

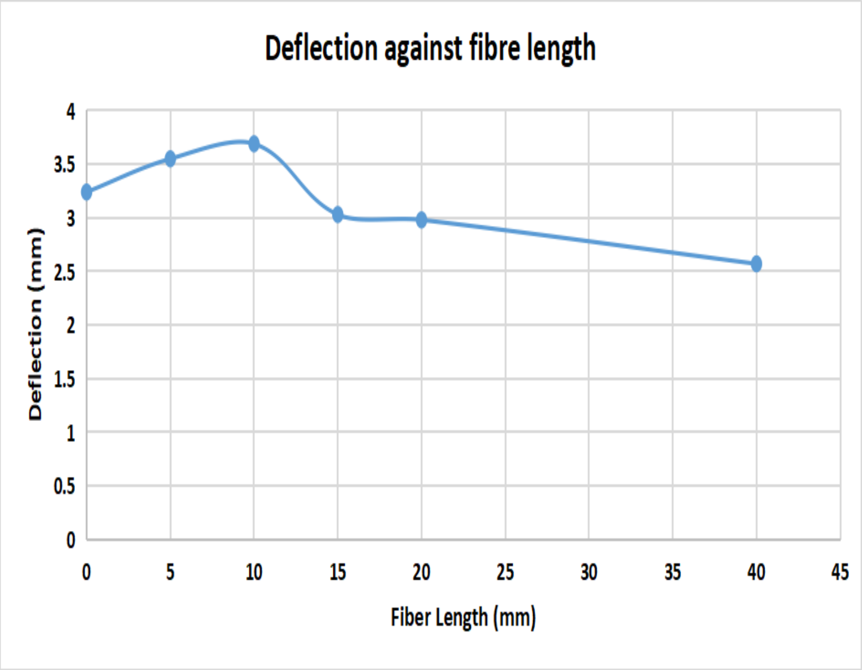
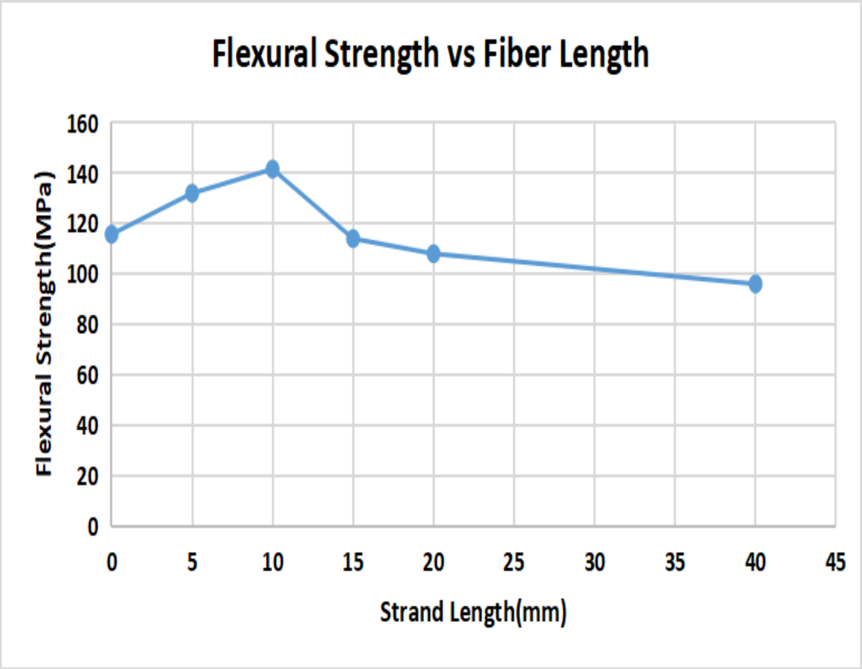


Figure 15 Graph of deflection vs fibre length

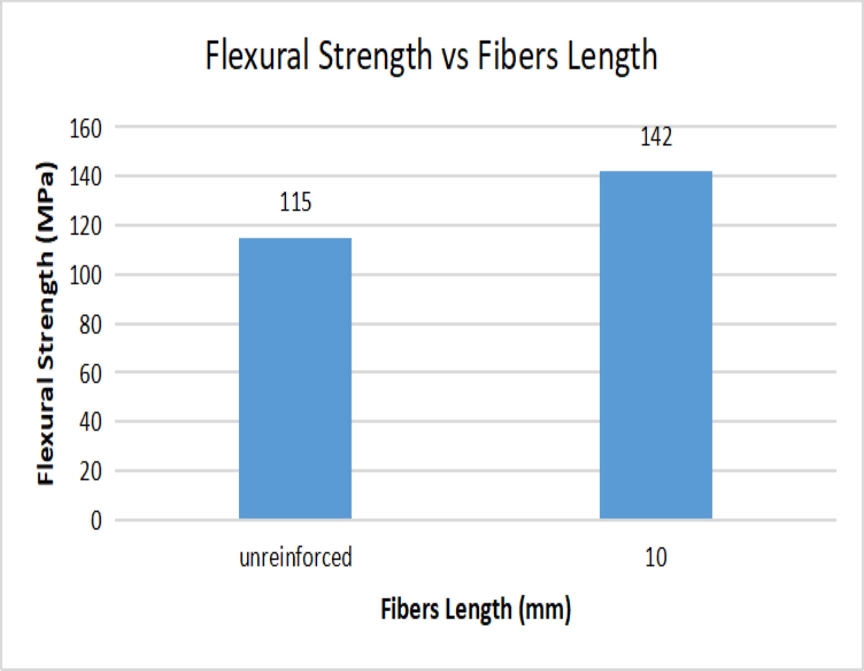
The flexural strength was calculated from the Eq. 1 and graph was plotted against different fibre lengths. The flexural strength of 115.7 MPa was obtained in case of unreinforced specimen. The maximum value of 141.6 MPa was obtained at 10 mm fibre length reinforced specimen however, further increase in fibre length resulted in reduction in the value of flexural strength. Minimum value of 96 MPa was obtained at fibre length of 40 mm Figure 16(a).

The flexural strength of specimens depends on the extend of load transmission along the length of the part and the magnitude. We have noticed an increase in flexural strength in the specimens with starting lengths of 5 mm and 10 mm is due to the fact that the transmission of load depends on length of fibres and magnitude of interfacial cohesion. Longer fibres resist deformation more as compared to shorter fibres due to the numerous fibre ends in short fibres which generate more friction (Mathew and Joseph, 2007). In our research 10 mm fibre lengths imparted maximum flexural strength and modulus. This is because the interaction between polymer matrix and glass fibres has got maximum degree at this length and load transmittance is also maximum. So, this 10 mm fibre length is the critical length and beyond this length the load transmittance decreases due to entanglement of fibres Figure 16 (b).

Glass fibres were cut into different lengths such as 5 mm, 10 mm, 15 mm, 20 mm and 40 mm to study their effect on the flexural strength of the specimens as Chollakup et al. presented in his research that fibre length have positive impact on the strength of composites for some nominal length of fibres (Chollakup et. al., 2011). It was observed that the flexural strength of fibre reinforced composite showed maximum at some nominal length of fibre strand in the research carried out by Garoushi and Coworkers (Garoushi et al, 2007). According to Avci et al., 2004 the flexural modulus as well as strength increases with increase in fibre length but up to an optimum limit after which they starts decreasing because of weak bonds present between fibres and resin (Avci et al., 2004).



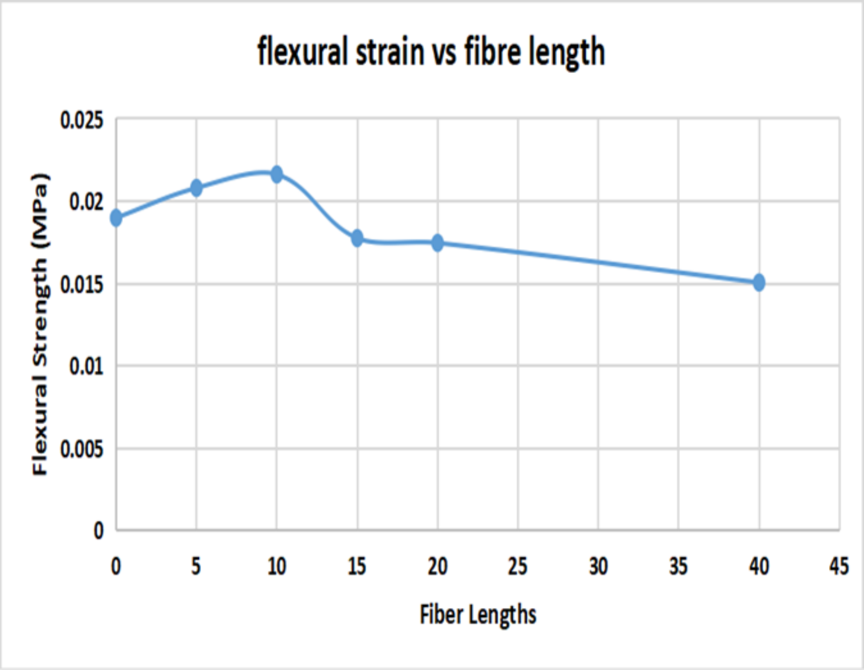
(a)



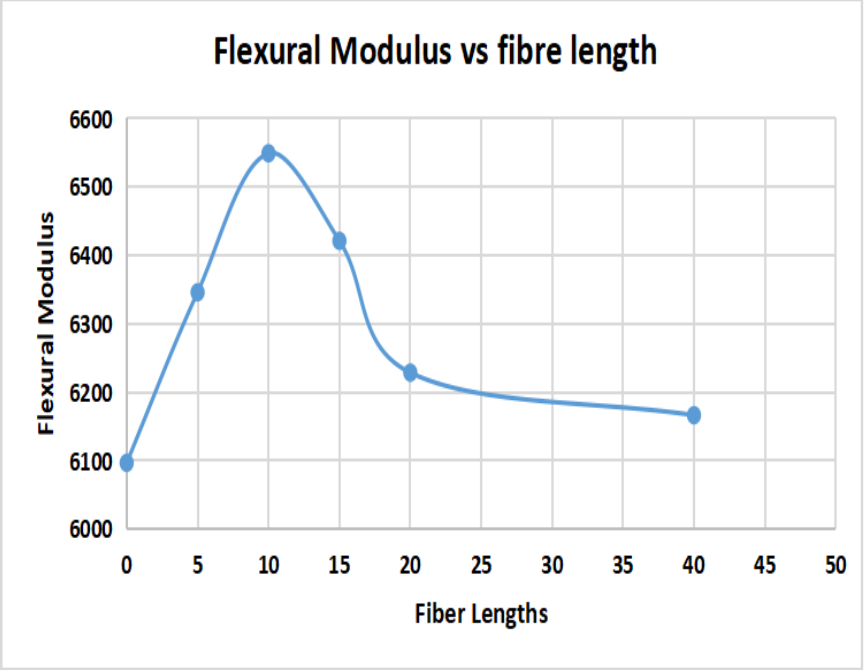
(b)

Figure 16 (a) Graph of flexural strength vs fibre length (b) Graph of comparison between unreinforced polymer and reinforced polymer with maximum strength length.

The flexural strain was calculated using Eq. 2 and the results are displayed in Figure 17 (a). The unreinforced specimen showed value of 0.019 MPa whereas the maximum value of 0.021 MPa was given by reinforced fibre with length of 10 mm. The minimum value of 0.015 was reflected by specimen of 40 mm fibre length. Determination of flexural strain through the equation is necessary in order to find out the flexural modulus of the specimens.



(a)



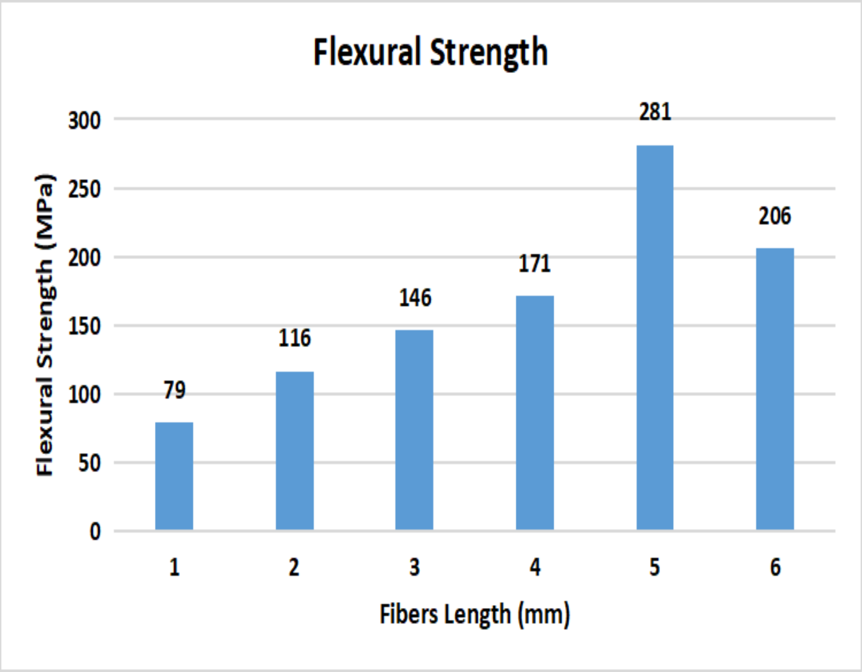
(b)

Figure 17 (a) Flexural strain against fibre lengths (b) Flexural modulus against fibre lengths

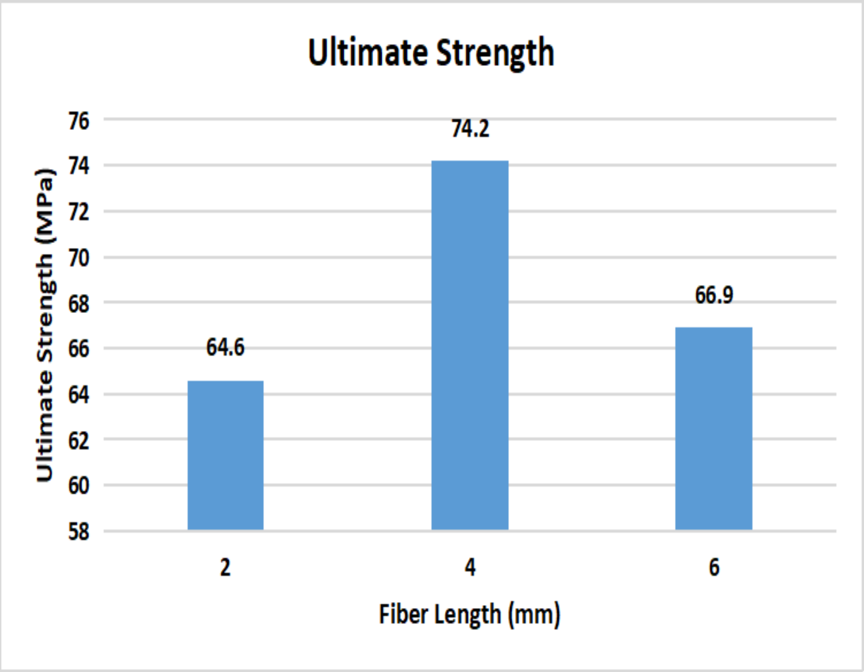
According to Eq. 3, the flexural modulus of 6064.7 MPa was obtained for unreinforced part. Increase in the trend was observed as the length of the fibres was increased from 0 to 10 mm and the maximum value of flexural modulus was 6549.1 MPa (Figure 4 b). At fibre length of 10 mm at which optimum modulus was observed, enables maximum transfer of stress from resin to reinforced fibre. This critical length also allows fibres to act as crack stoppers.

To validate the results consider the research presented by Garoushi and his coworkers. They prepared six glass fibre reinforced specimens polymers with fibre lengths of 1 to 6 mm and found out their flexural strengths as 79, 116, 146, 171, 281 and 206 MPa. They found that the flexural strength initially increases from 1 to 5 mm and then decreases by increasing fibre length. So 5 mm is the critical fibre length for maximum flexural strength as shown in Figure 6 (Garoushi et al., 2006). Capela et al. also studied the effect of fibre lengths (2,4 and 6 mm) on the ultimate strength and found that initially for 2 and 4 mm length the strength increases but it decreases for higher value of 6 mm so 4 mm is the critical length (Capela et al., 2006).

The graphs of both the researches are shown in Figure 18 (a) and (b).



(a)



(b)

Figure 18 (a) Effect of Fibres Length on Flexural Strength by Garoushi et al. (b) Effect of Fibres Length on Ultimate Strength by Capela et al.

CHAPTER 5

CONCLUSION AND FUTURE RECOMMENDATIONS

Conclusion

This study demonstrated the effect of addition of glass fibres and their length on the flexural strength of polymer composite. SLA 3d printer was used to manufacture glass fibre reinforced photosensitive polymer resin so to investigate their flexural properties. One unreinforced specimen was prepared along with the five reinforced specimens of different fibre lengths i.e. 5, 10, 15, 20 and 40 mm. The 3-point bend test was performed on all the specimens and flexural properties were compared. The summary of findings is given below:

- Flexural Strength was increased after reinforcing the glass fibres in SLA manufactured part as compare to unreinforced part.
- Increase in flexural strength was observed for initial fibre lengths of 5 and 10 mm fibres as compared to unreinforced polymer specimen. As fibre length increased, a lower strength was seen. So 10 mm is considered optimum fibre length for maximum flexural strength.
- The flexural modulus has the same trend like the flexural strength. It showed maximum value at 10 mm fibre length and then decreases for greater lengths.

Future Recommendations

The Flexural properties of short glass fibre reinforced polymers manufactured through SLA 3D printer can be further enhanced by improving the hand laying method and by proper post process of the part.

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