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Experimental Validation of 3-D Printed Bolts

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ABSTRACT: *3-D printing, which is an automated production process with layer-by-layer control, has been gaining rapid development in recent years. 3-D printing is the process by which a 3-D digital design is converted into a component by depositing material using additive processing. Three dimensional (3D) printing offers versatile possibilities for adapting the structural parameters on engineering scaffolds. These three dimensional elements were produced from Poly Lactic Acid (PLA) and Acrylonitrile butadiene Styrene (ABS)by means of fused deposition process. This work is initiated by designing a three dimensional model of an ISO standard bolt and creating a 3D printing of this model using PLA and ABS as material. Designing will be carried out using SOLIDWORKS. Later on the design is analysed on analysis software (ANSYS) for deformation, equivalent stress and shear stress. A prototype model of this bolt will be created using three dimensional printer. Shear test is performed using UTM on the bolts that are created using three dimensional printer. Each bolt material's failure forces are noted down and shear stresses are calculated. The PLA and ABS bolts are compared with each other. They are also checked for safe limits by comparing them with their respective material properties.*

Keywords:*3-D printing, Bolts,PLA.*

I. INTRODUCTION

3D printing, also known as additive manufacturing (AM), refers to processes used to synthesize a three-dimensional object in which successive layers of material are formed under computer control to create an object. Objects can be of almost any shape or geometry and are produced from digital model data 3D model or another electronic data source such as an Additive Manufacturing File (AMF) file.

The term 3D printing has its origin sense, 3D printing in reference to a process that deposits a binder material onto a powder bed with inkjet printer heads layer by layer. More recently, the term is being used in popular vernacular to encompass a wider variety of additive manufacturing techniques. United States and global Technical standards use the official term additive manufacturing for this broader sense. ISO/ASTM52900-15 defines seven categories of AM processes within its meaning: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination and Vat Photo polymerization.

The manual modeling process of preparing geometric data for 3D computer graphics is similar to plastic arts such as sculpting. 3D scanning is a process of collecting digital data on the shape and appearance of a real object, creating a digital model based on it. Before printing a 3D model from an STL file, it must first be examined for errors. Most CAD applications produce errors in output STL files: holes, faces normal, self-intersections, noise shells or manifold errors.A step in the STL generation known as "repair" fixes such problems in the original model. Generally STLs that have been produced from a model obtained through 3D scanning often have more of these errors. This is due to how 3D scanning works-as it is often by point to point acquisition, reconstruction will include errors in most cases.Computer-aided design (CAD) is the use of computer systems to aid in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for print, machining, or other manufacturing operations. The term CADD (for Computer Aided Design and Drafting) is also used.

Once completed, the STL file needs to be processed by a piece of software called a "slicer," which converts the model into a series of thin layers and produces a G-code file containing instructions tailored to a specific type of 3D printer (FDM printers). This G-code file can then be printed with 3D printing client software (which loads the G-code, and uses it to instruct the 3D printer during the 3D printing process).A so-called slicer takes a 3D drawing (most often in .STL format) and translates this model into individual layers. It then generates the machine code that the printer will use for printing. In this work after printing the bolt is the preferred for making a joining and is tested under analysis software and under UTM for failure.

II.DESIGN

The designing bolts and nuts are done using Solidworks®. SOLIDWORKS® Industrial Designer (SWID) is a concept design tool that allows oneto quickly generates multiple industrial design concepts in response to a design brief. It offers unique tools for the rapid creation, manipulation, and modification of designs using native and imported geometry. A screwed joint is mainly composed of two elements i.e. a bolt and nut. The screwed joints are widely used where the machine parts are required to be readily connected or disconnected without damage to machine or fastening. This may be for the purpose of holding or adjustment in assembly or service inspection, repair, or replacement or it may be for the manufacturing or assembly reasons. When a bolt is subjected to shock loading, as in case of a cylinder head bolt of an IC engine, the resilience of bolt should be considered in order to prevent breakage at the thread. In an ordinary bolt, as in figure below, the effect of impulsive loads applied axially in concentrated on the weakest part of the bolt i.e. the cross sectional area at the root of the threads.

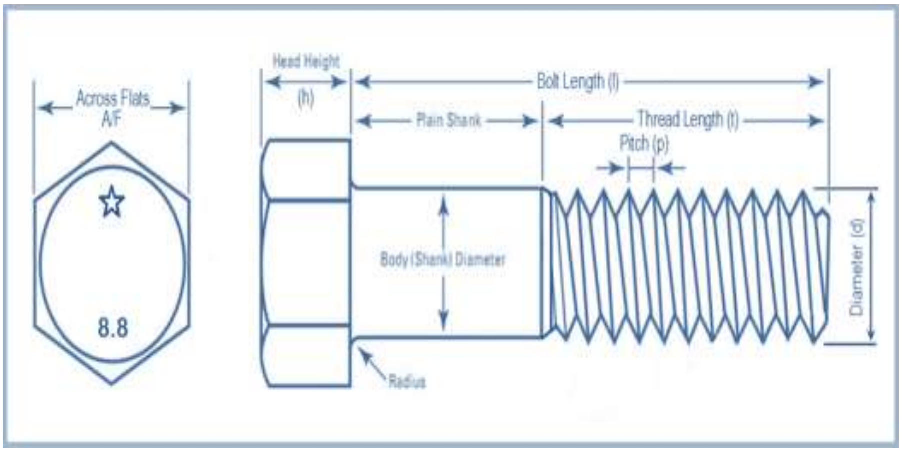


Fig 1: bolt nomenclature

Hence, a great potion of energy will be absorbed at the region of threaded part which may fracture the threaded portion because of its small length.If the shank of the bolt is turned down to a diameter equal or even less than the core diameter of the thread as shown below, then shank of bolt will undergo a higher stress. This means that shank will absorb a large portion of energy, thus relieving the material at sections near the thread. The bolt in this way becomes stronger and lighter and it increases the shock absorbing capacity of the bolt because o an increased modulus of resilience. This gives us bolts of uniform strength.

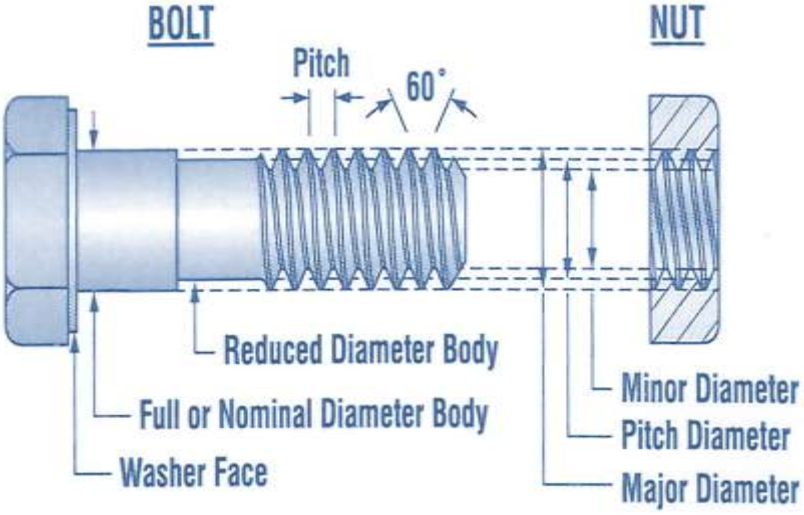


Fig 2: bolt nomenclature

Table 1: Bolt Specification

Designation	Pitch	Major or nominal diameter Nut and Bolt
M12	1.75	12.00

Design of Bolt and Nut in solid work

Fig 3: bolt in Solid works

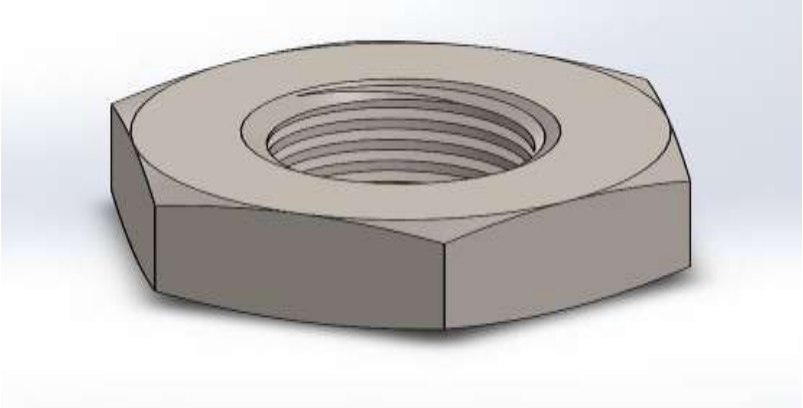


Fig 4: Nut in Solid works

III. SLICING AND CURA

There are two major types of software that will allow printing a (good read-to-print) 3D model file:A so-called slicer takes a 3D drawing (most often in .STL format) and translates this model into individual layers. It then generates the machine code that the printer will use for printing.3D printers can be either controlled through a small on-board control screen or through a (USB) interface with a computer or through both. User interface/control software allows a user to send a machine code file from the computer to the 3D printer, change some parameters on run time (e.g. speed, flow and temperature), and move the print head manually around the x/y/z axisSome programs, like the Netfabb engine, combine the functionality of a slicer and a user interface/control software. In addition programs like Netfabb engine, can add STL editing, repairing, merging and some simple 3D modeling.CuraEngine is a powerful, fast and robust engine for processing 3D models into 3D printing instruction for Ultimaker and other GCode based 3D printers. It is part of the larger open source project called "Cura".The CuraEngine is a C++ console application for 3D printing GCode generation. It has been made as a better and faster alternative to the old Skeinforge engine.The CuraEngine is pure C++ and uses Clipper from http://www.angusj.com/delphi/clipper.php Furthermore it depends on libArcus by Ultimaker. This library contains C++ code and Python3 bindings for creating a socket in a thread and using this socket to send and receive messages based on the Protocol Buffers library. It is designed to facilitate the communication between Cura and its backend and similar code.This is just a console application for GCodegeneration.This powerful program is one of the very best in the industry. It has two settings, simple and advanced, that tailor the program to your skill level. In simple mode, oneonly see essential settings such as infill type, filament type and support structure type. In advanced mode, onesee options for layer height, speed, cooling, social modes, platform adhesion and more. In both modes, hovering over a setting describes its function and recommended inputs. Cura and the Ultimaker 2+ are the ideal combination of printer and software for any custom project or skill level.

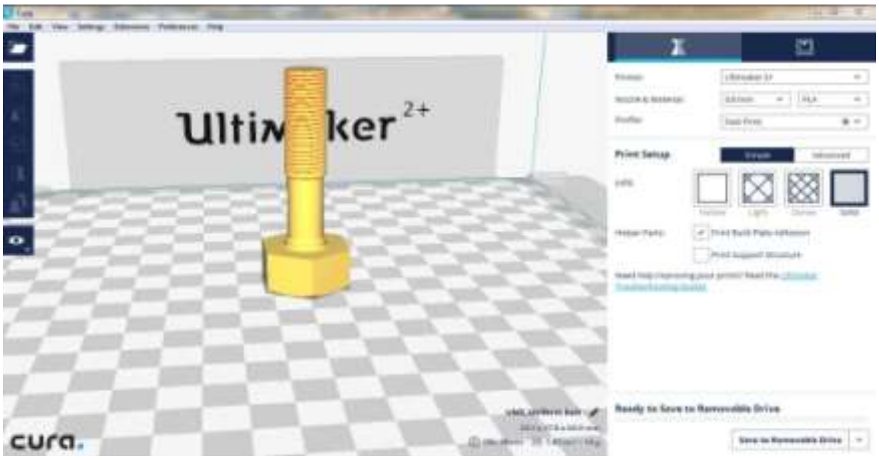


Fig 5: Slicing of bolt

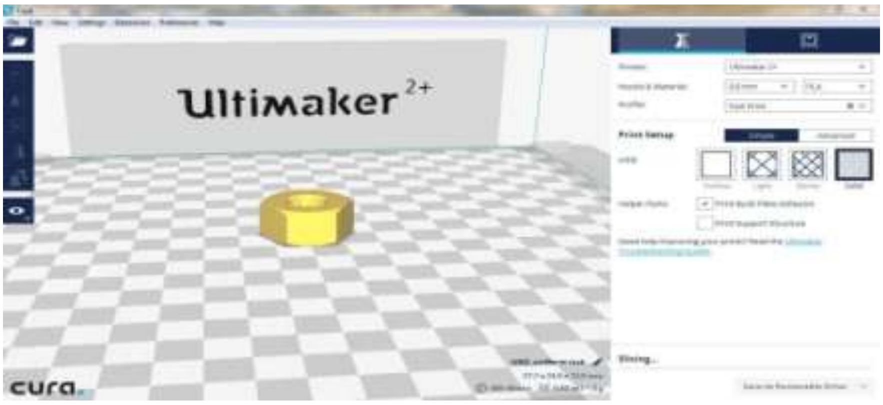


Fig 6: Slicing of nut

IV. MATERIAL AND ITS PROPERTIES

Pla:Poly(lacticacid) or polylactic acid or polylactide (PLA) is a biodegradable and bioactive thermoplastic aliphaticpolyester derived from renewable resources, such as corn starch (in the United States and Canada), tapioca roots, chips or starch (mostly in Asia), or sugarcane (in the rest of the world). In 2010, PLA had the second highest consumption volume of any bioplastic of the world.Producers have several industrial routes to usable (i.e. high molecular weight) PLA. Two main monomers are used: lactic acid, and the cyclic di-ester, lactide. The most common route to PLA is the ring-opening polymerization of lactide with various metal catalysts (typically tin octoate) in solution, in the melt, or as a suspension. The metal-catalyzed reaction tends to cause racemization of the PLA, reducing its stereo regularity compared to the starting material (usually corn starch). Another route to PLA is the direct condensation of lactic acid monomers. This process needs to be carried out at less than 200 °C; above that temperature, the entropicallyfavoredlactide monomer is generated. This reaction generates one equivalent of water for every condensation (esterification) step, and that is undesirable because water causes chain-transfer leading to low molecular weight material. The direct condensation is thus performed in a stepwise fashion, where lactic acid is first oligomerized to PLA oligomers. Thereafter, polycondensation is done in the melt or as a solution, where short oligomeric units are combined to give a high molecular weight polymer strand. Water removal by application of a vacuum or by azeotropic distillation is crucial to favorpolycondensation over transesterification. Molecular weights of 130 kDa can be obtained this way. Even higher molecular weights can be attained by carefully crystallizing the crude polymer from the melt. Carboxylic acid and alcohol end groups are thus concentrated in the amorphous region of the solid polymer, and so they can react. Molecular weights of 128–152 kDa are obtainable thus.

Polymerization of a racemic mixture of L- and D-lactides usually leads to the synthesis of poly-DL-lactide (PDLLA), which is amorphous. Use of stereospecific catalysts can lead to heterotactic PLA which has been found to show crystallinity. The degree of crystallinity, and hence many important properties, is largely controlled by the ratio of D to L enantiomers used, and to a lesser extent on the type of catalyst used. Apart from lactic acid and lactide, lactic acid *O*-carboxyanhydride ("lac-OCA"), a five-membered cyclic compound has been used academically as well. This compound is more reactive than lactide, because its polymerization is driven by the loss of one equivalent of carbon dioxide per equivalent of lactic acid. Water is not a co-product. The direct biosynthesis of PLA similar to the poly(hydroxyalkanoate)s has been reported as well.Amycolatopsis and Saccharotrix are able to degrade PLA. A purified protease from Amycolatopsis sp., PLA depolymerase, can also degrade PLA. Enzymes such as pronase and most effectively proteinase K from Tritirachium album degrade PLA. Pure PLLA foams undergo selective hydrolysis when placed in an environment of Dulbecco’s modified Eagle's medium (DMEM) supplemented with fetal bovine serum (FBS) (a solution mimicking body fluid). After 30 days of submersion in DMEM+FBS, a PLLA scaffold lost about 20% of its weight.

Table 3: Material properties of PLA

Density	1.3 g/cm^3 (81 lb/ft^3)
Elastic (Young's, Tensile) Modulus	3.5 GPa (0.51 x 10^6 psi)
Elongation at Break	6.0 %
Flexural Modulus	4.0 GPa (0.58 x 10^6 psi)
Flexural Strength	80 MPa (12 x 10^3 psi)
Glass Transition Temperature	60 °C (140 °F)
Heat Deflection Temperature	At 455 kPa (66 psi)65 °C (150 °F)
Melting Onset (Solidus)	160 °C (320 °F)
Shear Modulus	2.4 GPa (0.35 x 10^6 psi)
Specific Heat Capacity	1800 J/kg-K
Strength to Weight Ratio	38 kN-m/kg
Tensile Strength: Ultimate (UTS)	50 MPa (7.3 x 10^3 psi)
Thermal Conductivity	0.13 W/m-K
Thermal Diffusivity	0.056 m^2/s

ABS: Acrylonitrile butadiene styrene (ABS) (chemical formula $(C_8H_8)_x\cdot(C_4H_6)_y\cdot(C_3H_3N)_z)$ is a common thermoplastic polymer. Its glass transition temperature is approximately 105 °C (221 °F). ABS is amorphous and therefore has no true melting point.ABS is a terpolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The proportions can vary from 15 to 35% acrylonitrile, 5 to 30% butadiene and 40 to 60% styrene. The result is a long chain of polybutadiene criss-crossed with shorter chains of poly(styrene-co-acrylonitrile). The nitrile groups from neighboring chains, being polar, attract each other and bind the chains together, making ABS stronger than pure polystyrene. The styrene gives the plastic a shiny, impervious surface. The polybutadiene, a rubbery substance, provides toughness even at low temperatures. For the majority of applications, ABS can be used between −20 and 80 °C (−4 and 176 °F) as its mechanical properties vary with temperature.

The properties are created by rubber toughening, where fine particles of elastomer are distributed throughout the rigid matrix.ABS is derived from acrylonitrile, butadiene, and styrene. Acrylonitrile is a synthetic monomer produced from propylene and ammonia; butadiene is a petroleum hydrocarbon obtained from the C4 fraction of steam cracking; styrene monomer is made by dehydrogenation of ethyl benzene — a hydrocarbon obtained in the reaction of ethylene and benzene.ABS combines the strength and rigidity of acrylonitrile and styrene polymers with the toughness of polybutadiene rubber. While the cost of producing ABS is roughly twice the cost of producing polystyrene, it is considered superior for its hardness, gloss, toughness, and electrical insulation properties.According to the European plastic trade association PlasticsEurope, industrial production of 1 kg (2.2 lb) of ABS resin in Europe uses an average of 95.34 MJ (26.48 kW·h) and is derived from natural gas and petroleum.ABS is stable to decomposition under normal use and polymer processing conditions with exposure to carcinogens well below workplace exposure limits.[19] However, at higher temperatures (400 °C) ABS can decompose into its constituents: butadiene (carcinogenic to humans), acrylonitrile (possibly carcinogenic to humans), and styrene.Concerns have been raised regarding airborne ultrafine particle (UFP) concentrations generated while printing with ABS, as UFPs have been linked with adverse health effects.

Table 4: Material properties of ABS

Density	1.0 to 1.4 g/cm^3 (62 to 87 lb/ft^3)
Dielectric Constant (Relative Permittivity)	At 1 Hz 3.1 to 3.2
Dielectric Strength (Breakdown Potential)	15 to 16 kV/mm (0.59 to 0.63 V/mil)
Elastic (Young's, Tensile) Modulus	2.0 to 2.6 GPa (0.29 to 0.38 x 10^6 psi)
Elongation at Break	3.5 to 50 %
Flexural Modulus	2.1 to 7.6 GPa (0.3 to 1.1 x 10^6 psi)
Flexural Strength	72 to 97 MPa (10 to 14 x 10^3 psi)
Heat Deflection Temperature	At 1.82 MPa (264 psi) 76 to 110 °C (170 to 230 °F)
Heat Deflection Temperature	At 455 kPa (66 psi)83 to 110 °C (180 to 230 °F)
Impact Strength: Notched Izod	70 to 370 J/m (1.3 to 6.9 ft-lb/in)
Rockwell R Hardness	100 to 110
Strength to Weight Ratio	37 to 79 kN-m/kg
Tensile Strength: Ultimate (UTS)	37 to 110 MPa (5.4 to 16 x 10^3 psi)
Thermal Expansion	81 to 95 µm/m-K

V. PRINTING

The Ultimaker 2+ stands out in our 3D printer comparison for its sleek design and interface, high print quality, and overall functionality. One can control print layer height and speed with the powerful Cura software, and the printer comes with multiple nozzles in different sizes to customize prints to ones individual needs. The Ultimaker 2+ can print layers as thin as 0.06 mm, which is less than the thickness of a piece of paper. We did notice some occasional issues common to 3D printers, including a little bit of layer shifting and ringing, but most prints were still successful. During our testing, the printer didn't have any problems with overheating on account of its smart fan placement, which improves the airflow throughout the interior. This 3D printer's excellent performance is only enhanced by the four different nozzles included with the initial purchase. Other 3D printers have one or two optional nozzle replacements and sizes available for purchase, but the Ultimaker's are easily swappable and completely free. The smallest size is 0.25 mm, and one can use it to print slow, high-quality models; the largest nozzle is 0.8 mm, and one can use it to boost ones print speeds and make draft-quality prints. One of the printer's only downsides is its small print space of 8.7 x 8.7 x 8 inches, which is only about average for 3D printers. It's more than enough space to print medium and small prints though. This compact home 3D printer is easy to connect to. While it doesn't have Wi-Fi, it does have an SD card slot so one can still print wirelessly.

If one has a dedicated computer, the Ultimaker 2+ also prints via a USB cable connection. Controlling this 3D printer is also super simple – the onboard screen lets one change all the settings and functions. One can use it to change filament, start and stop prints, level the bed, change the temperature, and more. While the screen is small, the scroll dial is large and easy to operate. It is observed that the time taken for printing of each bolt is 4 to 5 hours when 0.4 mm nozzle diameter is used. Increasing the nozzle diameter reduces the time taken for printing but it also decreases the accuracy of the model and vice versa is also true. While the manufacturing of the nut takes about an hour. Continuous power supply is required for printing of any model. If any disturbances occur in such case the printing is not resumed and has to be started over from the beginning, thus there will be wastage of material and loss of time. It is necessary that the print surroundings is dust free and clan to avid blockage of nozzle and for obtaining a better model. Before printing one should check the glass plate is clean. As the printing is about to start light adhesive material is to be applied over the glass plate so that the print bacterial sticks to the base plate and does not come off after it gets dry while printing.

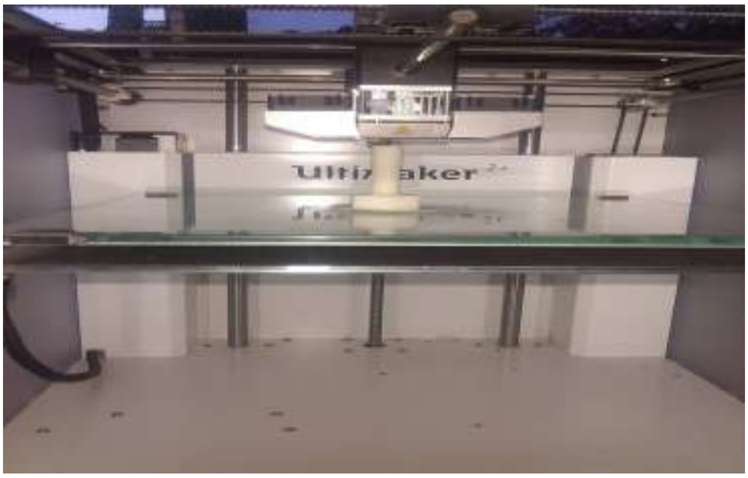


Fig 7: Printing with ABS

Fig 8: Printing with PLA

VI. ANALYSIS

ABS Analysis

Joint formation

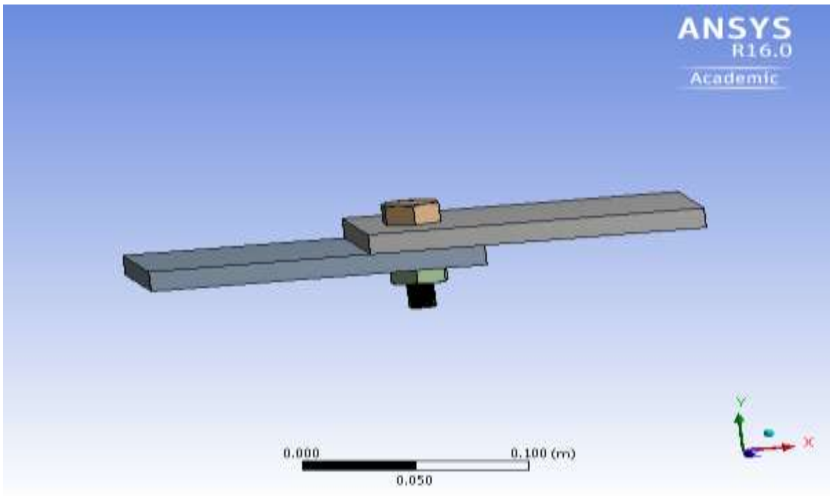


Fig 9: joining of bolt with work pieces

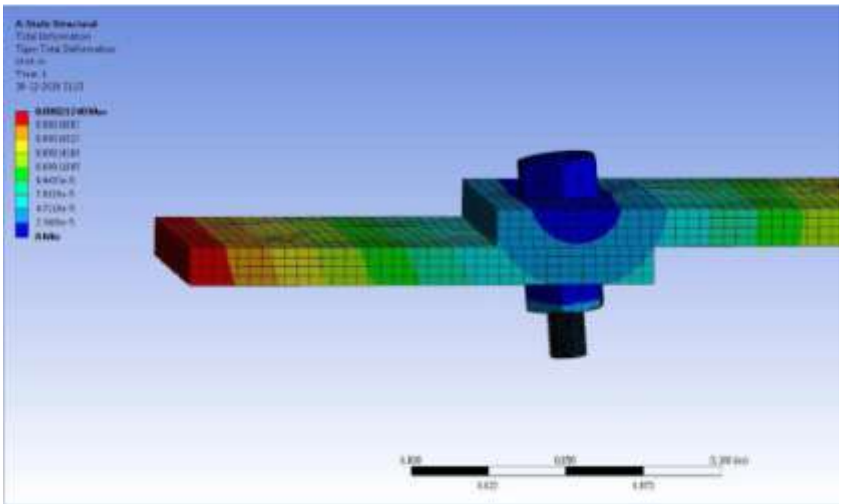


Fig 10: Total deformation

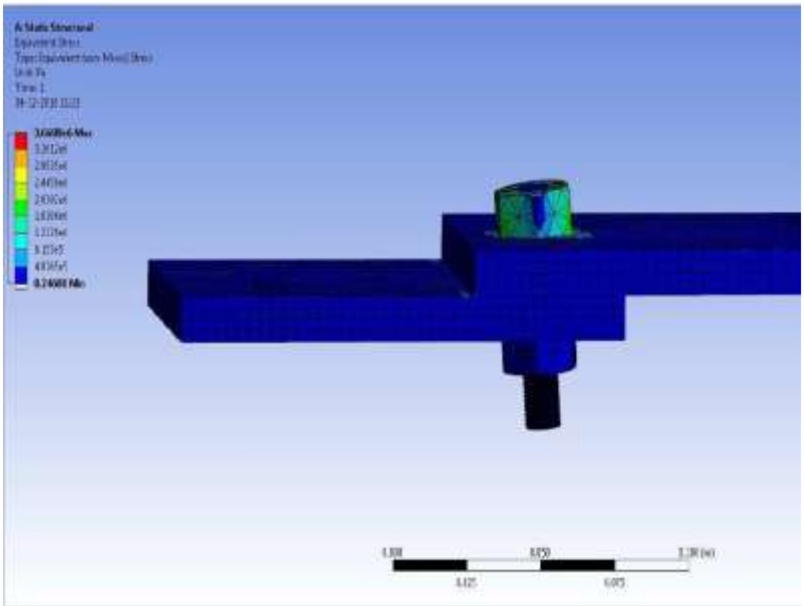


Fig 11: Equivalent Stress or Von Mises Stress

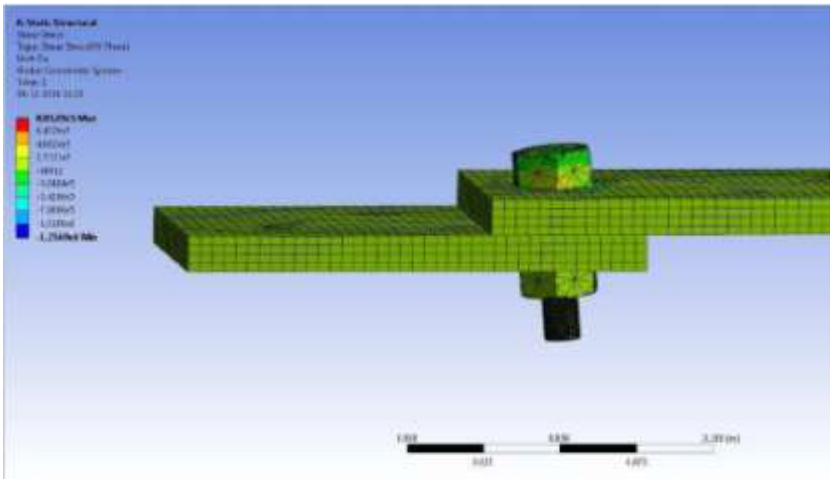


Fig 12: Shear Stress

Pla

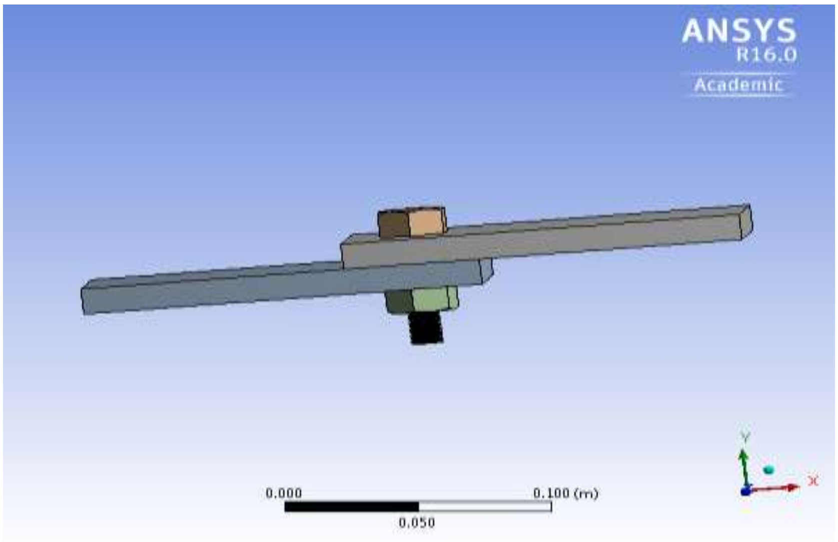


Fig 13: joining of bolt with work pieces

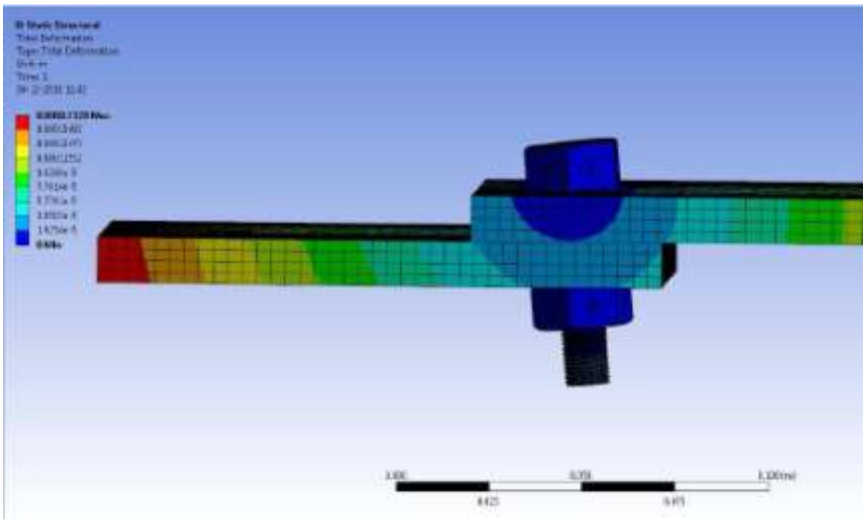


Fig 14: Total deformation

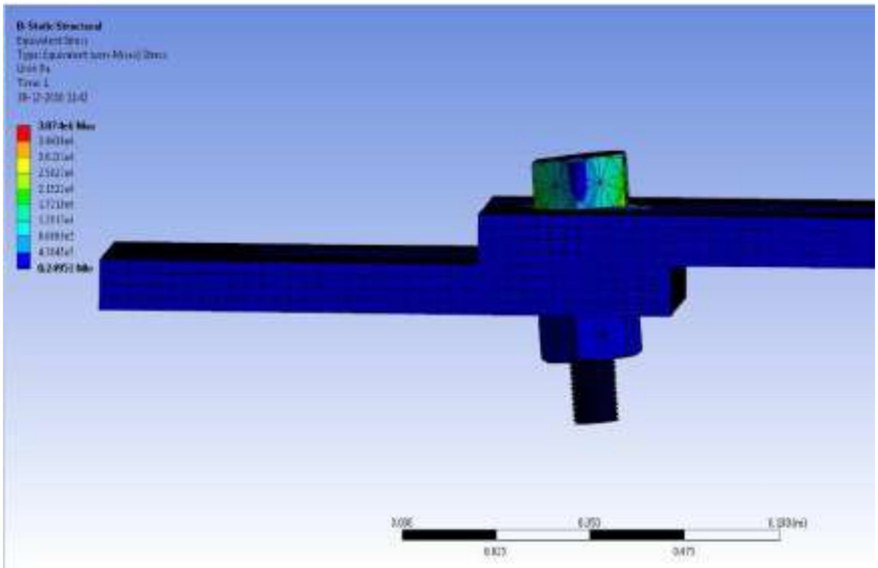


Fig 15: Equivalent Stress or Von Mises Stress

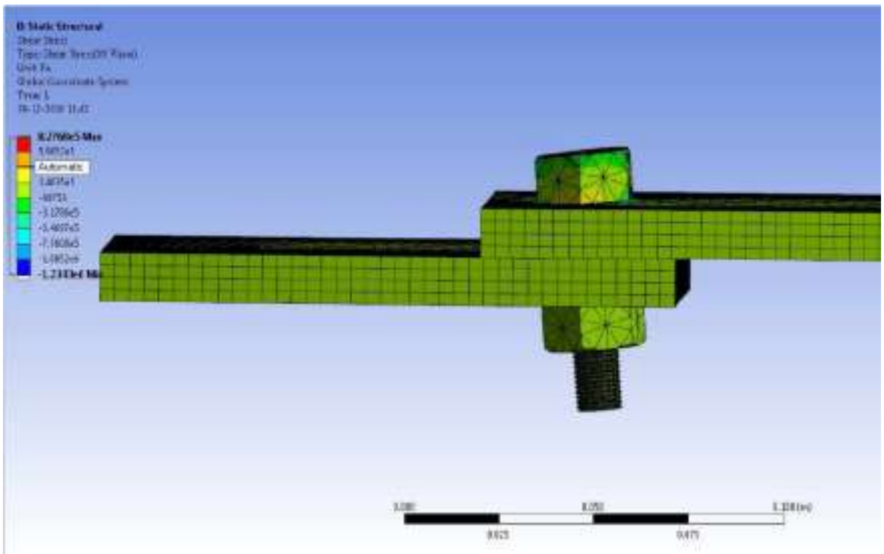


Fig 16: Shear stress

VII. TESTING

Destructive testing of both the materials i.e. PLA and ABS, are performed using UTM (Universal Testing Machine). The bolts are tested for shear by fastening them to two wooden (plywood) pieces of dimension 18mm x 60mm x 200mm lap jointed together.The plywood pieces pulled causing tension in the plywood and shearing in the bolts. The forces are applied on the plywood until failure occurs in the bolts. The break point or failure point is obtained for each type of bolt material.Through hole of diameter 12.5mm is made.

Fig 17: Wood work pieces

Fig 18: Wood work pieces joint with bolt and nut

Fig 19: Wood work pieces joint with bolt and nut in UTM

VII. CALCULATION

Pla

Ultimate tensile strength (UTS) = 50MPa

Ultimate shear strength (USS) = $\frac{UTS}{2}$

=25MPa

Allowable Stress = 15% of USS = 3.75MPa
Force at which failure occurs = 0.3KN
=0.3×10^3 N
Diameter of bolt, D = 9.858mm
Area under stress, A = $\frac{\pi}{4}D^2$
Shear stress, $\tau = \frac{Force}{Areaunderstress}$
$= \frac{0.3 \times 10^3}{\frac{\pi}{4} \times 9.858^2}$
=3.93 N/mm²
τ = 3.93 MPa
Factor of safety = $\frac{Failurestress}{Allowablestress} = \frac{3.93}{3.75}$ = 1.04

Size factor = 0.85 (for 7.5< d ≤ 50)
Stress concentration factor = 1.4 (for $\frac{D}{d}$= 1.2, $\frac{r}{d}$= 0.202)

ABS

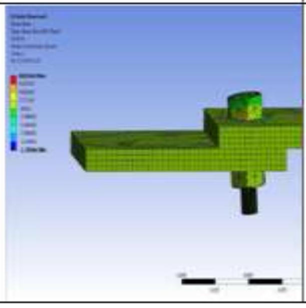
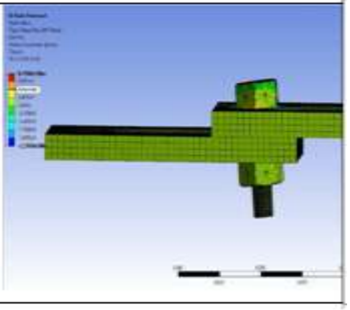
Ultimate tensile strength (UTS) = 37MPa

Ultimate shear strength (USS) = $\frac{UTS}{2}$
=18.5MPa
Allowable Stress = 15% of USS = 2.775MPa
Force at which failure occurs = 0.27KN
=0.27×10^3 N
Diameter of bolt, D = 9.858mm
Area under stress, A = $\frac{\pi}{4}D^2$
Shear stress, $\tau = \frac{Force}{Areaunderstress}$
$= \frac{0.27 \times 10^3}{\frac{\pi}{4} \times 9.858^2}$
=3.53 N/mm²
τ = 3.53 MPa
Factor of safety = $\frac{Failurestress}{Allowablestress} = \frac{3.53}{2.775}$ = 1.27

Size factor = 0.85 (for 7.5< d ≤ 50)
Stress concentration factor = 1.4 (for $\frac{D}{d}$= 1.2, $\frac{r}{d}$= 0.202)

IX. RESULT AND DISCUSSION

	Properties	ABS	PLA
Experimental Analysis	Failure force	270N	300N
	Shear stress	3.5Mpa	3.9Mpa
	Stress concentration factor	1.4	1.4
	Maximum Stress	4.95Mpa	5.5Mpa
	UTM analysis		

Theoretical Analysis (ANSYS)	Failure force	270N	300N
	Shear Stress	3.69Mpa	4.1Mpa
	Equivalent Stress	3.6Mpa	3.87Mpa
	Ansys result		

Comparing yield strength with analysis results shows that the equivalent stresses are less than the yield strength of the material. Thus the stresses are within the safe limits.
3.6MPa < 51.1MPa (for ABS)
3.87MPa < 71.7MPa (for PLA)

300N force is applied in shear for analysis of bolts. It is seen that the deformation of ABS is more than that of PLA for the same force. That means the failure of ABS occurs with less force when compared with that of PLA.Similar results are obtained in the actual testing of bolts. That is, the failure of ABS bolt occurs at a force of 270N and the failure of PLA bolts occurs at a force of 300N. The shear stress for ABS bolts and PLA bolts are calculated and obtained as 3.53MPa and 3.93MPa respectively. Thus ABS material is weaker in shear than PLA material. It can be noted that the shear stress obtained in testing is approximately equal to equivalent stress obtained from the analysis.The factor of safety obtained for PLA is 1.02 while the factor of safety for ABS is 1.27.

X. CONCLUSION

3D printing of ISO standard M12 bolts is printed using PLA and ABS materials. These bolts are tested for failure force under shear. The designing and analysis of bolt and nut is done using SOLIDWORKS and ANSYS respectively. The printed bolts are also tested under UTM for obtaining the failure force in shear. After the analysis and testing it can be concluded that the bolts made of PLA material are stronger in shear having factor of safety 1.02 when compared to that of bolts that are made of ABS material having factor of safety 1.27.

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